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REPLACEMENT CAPABILITY OPTIONS FOR THE UNITED STATES SPACE SHUTTLE

by

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September 2013

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After having invested millions of dollars into the International Space Station (ISS) and retiring the Space Shuttle, NASA and the U.S. are in the rare position of not having an operational human space lift program to reach the ISS or any location in space. This is truly an unusual time period in the history of NASA manned spaceflight. This thesis addresses the human spaceflight, Up Mass (launch a payload into space), and Down Mass (return payload from space) capabilities of the U.S. Space Shuttle and assesses options to regain these capabilities now that the Space Shuttle is retired. The research in this thesis was done with unclassified and public-domain information and was used to evaluate and propose options for mitigating the capability gaps left by the end of the United States Space Shuttle program. No current or planned system can fulfill all the capabilities that the Space Shuttle was able to provide. However, there are current/future domestic and foreign systems that can or will address these capabilities individually.

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REPLACEMENT CAPABILITY OPTIONS FOR THE UNITED STATES SPACE SHUTTLE

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ABSTRACT

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I. INTRODUCTION

A. BACKGROUND

NASA human space flight programs have always been a source of national pride and a source of innovation for the United States. As the U.S. initially strived to reach the moon and later explored space using the Space Shuttle, it has been a leader in space travel and exploration. Beyond national pride, Americans have collectively benefited from the technologies developed from manned space flight technologies. Pumps found in artificial hearts, cordless power tools, medical imaging diagnostic machines, microwave ovens, various lubricants, and memory foam are representative of the inventions that originated from NASA space programs. Consumer products, transportation, public safety, health and medical science have all benefited from the United States having a manned space program (NASA, 2011).

On October 22, 2009, NASA hosted a press conference to present the U.S. Human Space Flight Review Committee Report. Human space flight was identified as an important and worthwhile venture for the United States. The research and technology development generated by human research make human space flight a priority for the United States and its space program. The committee proposed options for the future and highlighted the importance of the International Space Station (ISS). Dr. Neil DeGrasse Tyson in his latest book, "Space Chronicles," states that "science and technology are the greatest engines of economic growth the world has ever seen." The Apollo, Space Shuttle, and International Space Station (ISS) programs have been significant economic engines for the U.S. economy. The United States has too much to lose by not continuing human space flight. Without it the U.S. will not have that source of economic growth, technological innovation, discovery, and national pride that it needs and desires. (NASA Public Affairs, 2009; Tyson, 2012)

The United States has made substantial investments into the Space Shuttle and the International Space Station programs. Over the course of 40 years and $196 billion, the U.S. designed and constructed five Space Shuttle orbiters that completed a total of 135

Space Shuttle flights. The fifth and last Space Shuttle orbiter, Endeavour, cost approximately $1.7 billion to construct. Excluding design, construction, and upgrade costs, the average operating cost of a Space Shuttle flight was $847 million. The United States, Russia, Europe, Canada and Japan are expected to have invested more than $100 billion into the ISS construction and operations by 2020. ISS operations, transportation and research costs alone are estimated to be more than $3 billion each year through 2020. As of July 2012, the ISS international partners had launched at total of 125 missions to the ISS: 81 Russian, 37 U.S. Space Shuttle, one U.S. commercial, three European, and three Japanese spacecraft missions. These investments point to the importance of space exploration and the Space Shuttle and ISS programs. (NASA, 2012; Svitak, 2012; NASA, 2008; Borenstein, 2011)

B. OBJECTIVES

This thesis addresses the human space flight capabilities, up mass and down mass aspects of the U.S. Space Shuttle program and assesses options to regain these capabilities now that the Space Shuttle is retired. After the United States' has invested two decades of development and engineering work, billions of dollars, and 37 Space Shuttle missions in designing, building and manning the International Space Station (ISS), the United States has committed to maintaining a presence in space and the ISS. With the end of the United States Space Shuttle program, the only option for the U.S. and other ISS partner nations is to fund the Russian government for seat(s) on a Soyuz rocket to transport crew members to and from the ISS. As was evident by the Columbia and Challenger tragedies, a single event can significantly impair or delay an entire space-lift capability. If the Soyuz had a similar incident, the international ISS team would be left with no options to launch and return crewmembers and would be unable to carry out the technical and scientific work done on the ISS. Also, if there is only a single system that can satisfy a critical need, then the U.S. and other ISS nations are at risk of being forced to pay whatever rate the commercial or foreign entity desires. The U.S. and other ISS nations are also at risk of not receiving a launch time they need or desire due to their priority or standing with the host nation or company. Availability of a system is an important aspect to consider when looking for ways to replace the capabilities the Space Shuttle provided. (Svitak, 2012)

Beyond having a single point of failure with reaching the ISS, the ISS will likely not be around for decades like Soyuz and the Space Shuttle. As the U.S. Human Space Flight Review Committee Report stated, the now cancelled Ares I program may not have been ready by the end of the ISS planned lifetime at the time of 2015. However, the ISS is now expected to be operational until to 2020. It is possible the lifespan of the ISS could be shortened or lengthened depending on condition/status of ISS and the financial standing of the ISS partner nations. It is also possible the ISS could be re-utilized or used by future commercial or government space programs. However as with all things in a low Earth orbit, without continued intervention the ISS will be destroyed when re-entering Earth atmosphere much like what happened to the U.S. Skylab and Russian space station Mir. Regardless of the length of the ISS service life; the U.S. will need a human space-lift capability after the ISS. (Svitak, 2012; U.S. Human Spaceflight Plans Committee, 2009; Kaplan, 2011)

The United States Space Shuttle program provided the U.S. a unique human space-lift capability; it provided capabilities no other previous system did or current systems do now. One of these unique capabilities was the Space Shuttle's ability to take a large amount of payload (in terms of both size and mass) into orbit along with its human passengers. The Space Shuttle's 15 foot by 60 foot cargo bay could carry between 18,300 and 28,800 kg of cargo into space depending on desired orbit altitude. This ability to take a payload into space is known as "Up Mass." Additionally the Space Shuttle had the ability to return a payload from space back to Earth known as "Down Mass." This Down Mass capability allows a spacecraft to take hardware, supplies, and scientific experiments from ISS back to Earth. The ability to return items from orbit allows for the repair and further scientific analysis of experiments that the scientists/astronauts may not have the time or equipment to do on orbit. The option to not have to do everything on orbit can save time and money, since the ISS partner nations don't have to pay to launch and build these Earth-based capabilities in space. (Isakowitz, Hopkins, & Hopkins, 2004; NASA, 2011)

C. RESEARCH QUESTION

With the United States Space Shuttle now retired, a number of questions have arisen. The answer to the first question provides a historical perspective of similar periods in which there was no U.S. human launch capability. The last three address how the United States can fill the capability gaps left by the Space Shuttle's retirement.

1. Have there been significant periods of time when the United States has been without a manned space flight capability since the U.S. began manned space missions? If so, what caused these gaps and how did they subsequently affect United States space flight programs?
2. What system(s) can replace the Space Shuttle's human space flight capability for the United States and safely transport Americans to and from space?
3. What system(s) can replace the Space Shuttle's large "Up Mass" payload-to-orbit capabilities in both size and mass for the United States?
4. What are the United States options for "Down Mass" items from space now that the Space Shuttle is unavailable?

D. SCOPE, LIMITATIONS AND ASSUMPTIONS

It is unclear what new space-lift technologies will be developed during this decade or how practical their applications might be for operational space-lift systems. Therefore, this thesis will focus on current systems, modification of current systems, and currently proposed or in development systems. Since many proposed space program concepts do not fully materialize, only those programs that are funded or have proceeded beyond the concept phase will be discussed. The ability of these systems to fully replace the payload and/or manned space flight lift capabilities of the Space Shuttle will be highlighted and investigated.

Since this thesis is to remain unclassified, the analysis will be dependent upon open source information provided by space-lift companies and government agencies (domestic and foreign). Changing political and foreign relationships are beyond the scope of this thesis. Therefore, it will be assumed that current relations status will continue. However, if the United States has a critical dependence on a capability, the relationship with the controlling party will be mentioned, but will not necessarily discussed in length.

E. LITERATURE REVIEW AND METHODOLOGY

This thesis was developed using the following literature review steps and methodology:

1. Conduct an open source review of space-lift and manned space flight capabilities program documentation.
2. Conduct a literature review for capability and comparison studies on current and planned programs that might be able to replace the capabilities provided by the U.S. Space Shuttle.
3. Contact space-lift manufacturers to gain additional insight into their system's capabilities and explore the ability to modify or upgrade systems if required.
4. Develop options/recommendations mitigating the U.S. capability gaps that have developed since the U.S. Space Shuttle retired.

F. DEFINITIONS AND ABBREVIATIONS

ISS is the abbreviation that will be used for the International Space Station.

The term "Space Shuttle" is used in this thesis to refer to the United States' Space Transportation System. It includes the entire system used to put an individual Space Shuttle Orbiter into space.

Up Mass is the term that will be used to describe the quantifiable ability to transport an object from the surface of the Earth and put it into an orbit around Earth (space).

Down Mass is the term that will be used to describe the quantifiable ability to return an object from an orbit around Earth (space) to Earth's surface

G. ORGANIZATION OF STUDY

Each of the following chapters will discuss a stated research question. The second chapter will discuss the history of the United States' human space flight programs and any capability gaps and their importance. This history is important to understand the reasons for the current inability of the United States to indigenously transport humans to space and how this inability is uncharacteristic of NASA based on it's history. Indigenous in this thesis refers to a system or capability being developed and controlled within an organization or nation. The capabilities of the Space Shuttle are also discussed in Chapter 2. Chapters 3 through 5 will discuss the United States' ability to replace the retired Space Shuttle's human space flight, Up Mass, and Down Mass capabilities, respectively. Chapter 3 will discuss the United States' options to continue human space flight missions to the ISS and to other destinations after the ISS is decommissioned. Chapter 4 will discuss options for the United States to transport items to Low Earth Orbit. Chapter 5 will discuss how the United States will be able to replace unique capabilities the Space Shuttle provided, such as the ability to resupply the ISS and return a large amount of mass to the Earth's surface. Chapter 6 will give a summary of findings and discuss the limitation of this thesis along with future work/research that may be needed.

II. UNITED STATES HUMAN SPACE FLIGHT

A. UNITED STATES HUMAN SPACE FLIGHT HISTORY

The U.S. has a long history of space flight through its space exploration agency, the National Aeronautics and Space Administration (NASA). NASA has had many human space flight programs in its storied history. The focus and driving force behind NASA's early human space flight programs was to first put an American in space and then to deliver a man to the moon and return him safely before the end of the 1960s. This goal was set by President Kennedy on 12 September 1961 during a speech delivered at Rice University, where he stated "We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win, and the others, too." In what would become known as the "Space Race," the Soviet Union and the United States competed to perform activities in space. On 12 April 1961, the Soviet Union's Vostok 1 rocket carried cosmonaut Yuri Gagarin into orbit, and the Soviet Union became the first country to place a human into space. However, at the same time the United States was pursuing its first human space flight program, the Mercury Program. On 05 May 1961, less then a month after the Soviet Union launched Yuri Gagarin, Alan Shepard launched aboard the Freedom 7 space capsule atop a Redstone rocket and became the first American in space. (Public Broadcasting Service, 2005)

The origin of the United States' human space flight launch capability can be traced back to Germany's V-2 rocket. The operational use of the V-2 by the Germans was limited to the end of World War II in the 1944 to 1945 time period. The creator of the V-2 was Wernher von Braun and his engineering team. He and 500 members of his team defected to the United States at the end of World War II and were brought to the U.S. under a military operation called Project Paperclip. Along with the engineering team, many captured V-2 rockets, parts and plans were also brought to the United States as well. Dr. Wernher von Braun, the other engineers, and V-2 items from Project Paperclip created the foundation for the United States' launch program. Dr. von Braun was the director of the NASA Marshall Space Flight Center from July 1, 1960 - Jan. 27, 1970. He was also the chief architect of the Saturn V launch vehicle. Dr. von Braun was therefore involved in all of NASA's early launch vehicles. Figure 1 shows Dr. von Braun's first rocket, the V-2, then the early NASA launch vehicles, Mercury, Gemini, and finally Apollo. (Marshall Space Flight Center History Office)

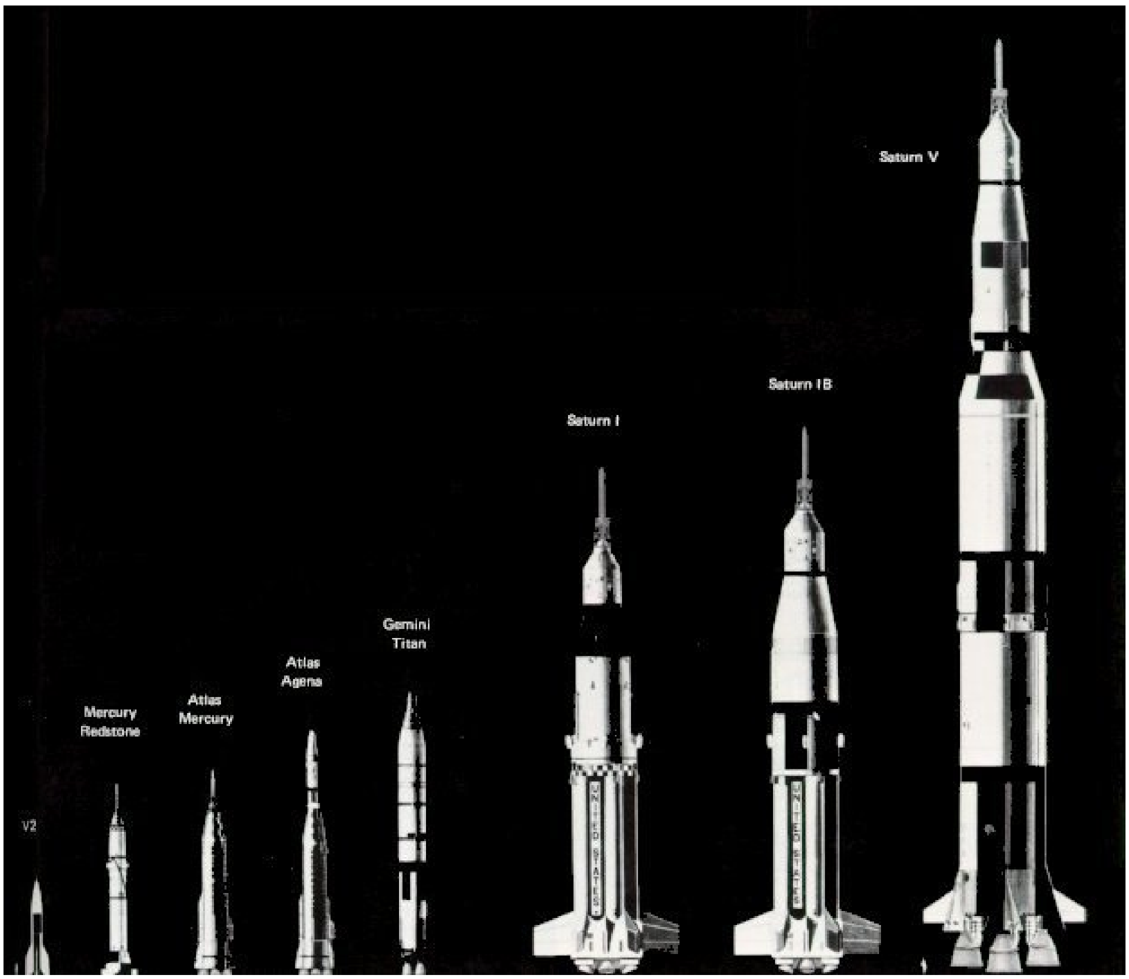

Figure 1. Early NASA Launch Vehicles (from Cortright, 1975)

All the rockets that were used by NASA to support manned space flight mission before the Space Shuttle are shown in Figure 1 with Dr. von Braun's V-2 added for size comparison. These early NASA launch vehicles include the Mercury program's Redstone and Atlas rockets (1961–1963), the Gemini program's Titian rockets (1965–1966), and the Saturn IV and V rockets used for the Apollo, Skylab, and Apollo-Soyuz Programs (1968–1975). The Atlas Agena was used to launch target objects with which some of the Gemini missions would dock. The Mercury, Gemini, and Apollo Programs will be discussed sequentially in the history section. These programs provide the history and show the gaps in NASA's manned space flight capabilities up to the beginning of the Space Shuttle program.

1. The Mercury Program (1961–1963)

NASA began U.S. human space flight efforts with the Mercury Program. From August 21, 1959 until November 29, 1961, twenty unmanned test flights were completed as part of the Mercury Program. The majority of these launches utilized the Little Joe, Redstone and Atlas launch vehicles. Only two of these launch vehicles the Redstone and Atlas, were later used for the Mercury Program's manned space flights. There was a slight overlap in unmanned and manned launches, due to the number of tests needed for each to receive certification for manned missions. The goals of the Mercury Program were: (Grinter, *The Mercury Project - Unmanned Missions*, 2000)

1.) To orbit a manned spacecraft around Earth,

2.) To investigate man's ability to function in space,

3.) To recover both man and spacecraft safely (Grinter, *The Mercury Project - Goals*, 2000).

NASA chose the U.S. Army's Redstone liquid-fueled ballistic missile for its manned sub-orbital flights. Due to the Redstone rocket's flight history, it was considered the most reliable of any U.S. ballistic missile at the time. The Mercury-Redstone Launch Vehicle was derived from the U.S. Army's Redstone ballistic missile, an improved engine which was the A-7, and the first stage of the related Jupiter-C launch vehicle. (Cassidy, Johnson, Leveye, & Miller, 1964)

The Atlas rocket, with a longer range than the Redstone rocket, was selected for the manned orbital flights of the Mercury Project. The Atlas rocket was the United States' first successful Intercontinental Ballistic Missile (ICBM). It was originally built for the United States Air Force to carry a nuclear warhead and was first flown in 1957. A newer version of the Atlas Missile, the Atlas D Missile, was modified to carry the Mercury Capsule. Both the Redstone and Atlas missiles required modification and flight-testing to carry their new payload, a manned capsule.

The first and shortest Mercury flight was on 05 May 1961. It utilized the Redstone Rocket and lasted only 15 minutes and 28 seconds. However this flight allowed its pilot, Alan Shepard, to become the first American in space. Even though this occurred after the first Soviet entered Earth orbit, it was an important step for the United States’ space flight program. Each successive Mercury launch lasted longer and set new endurance records for American astronauts. The third mission and first manned mission of the more powerful and capable Atlas rocket launch allowed John Glenn to become the first American to orbit the Earth. After 3 orbits, he returned to Earth on 20 February 1962. The final flight and longest Mercury mission lasted 34 hours, 19 minutes, 49 seconds or 22.5 orbits around the Earth. Gordon Cooper landed this spacecraft on 16 May 1963 and became the first American to spend over one day in space. In total there were six manned launches during the Mercury Program. They are shown in the following Table 1. (Grinter, *The Mercury Project - Flight Summary*, 2000)

Rocket	Launched	Returned	Mission	Duration
Redston	5-May-61	5-May-61	Mercury-Redstone 3	15 min, 28 sec
Redston	21-Jul-61	21-Jul-61	Mercury-Redstone 4	15 min, 37 sec
Atlas	20-Feb-62	20-Feb-62	Mercury-Atlas 6	04 hrs, 55 min 23 sec
Atlas	24-May-62	24-May-62	Mercury-Atlas 7	04 hrs, 56 min, 5 sec
Atlas	3-Oct-62	3-Oct-62	Mercury-Atlas 8	09 hrs, 13 min, 11 sec
Atlas	15-May-63	16-May-63	Mercury-Atlas 9	34 hrs, 19 min, 49 sec

Table 1. Manned Mercury Program Launches (after Grinter, *The Mercury Project - Flight Summary*, 2000)

The Mercury Program was a success and achieved the established goals resulting in the first planned gap in U.S. human space flight. With the success of the Mercury Program, the United States needed to move on to the next chapter of its manned space flight history. The Mercury capsules only had room for one person. If the United States was to land an American on the Moon, the ability to launch multiple astronauts into space at the same time was required. NASA was already working on this capability before the Mercury Program ended. Less then one year would elapse from the last Mercury launch and the first launch of the Gemini Program.

2. The Gemini Program (1965–1966)

The Gemini Program was announced in January 1962 and would double the number of astronauts being launched. The objectives of the Gemini Program were:

1.) “To subject men and equipment to space flight up to two weeks in duration.

2.) To rendezvous and dock with orbiting vehicles and to maneuver the docked combination by using the target vehicle's propulsion system;

3.) To perfect methods of entering the atmosphere and landing at a preselected point on land.” (Grinter, *Goals of the Gemini Program*, 2000)

It is worth noting that the third objective was never fully met as all NASA programs landed on water until the Space Shuttle program. There were two main components to each Gemini launch vehicle. The largest component was the actual rocket that would propel the second component, the space capsule, into space. These space capsules were located on top of the rocket in all early NASA launch vehicles. Though the space capsules were rather small compared to the rockets that launched them, they were very complex and important. The space capsule housed the astronaut(s) during all phases of flight (lift off, space travel, re-entry and landing back on Earth). All life support systems to keep the astronauts alive were incorporated into these space capsules. One of the main differences between the Gemini and Mercury programs was the size of their space capsule. The Mercury program's capsule was designed to only be able to hold one astronaut while the Gemini capsule was designed to be larger and carry two astronauts at the same time. Due to the larger space capsule and extra astronaut, the Redstone and Atlas rockets were not large enough to launch the Gemini capsule. Therefore, the Gemini program needed a larger rocket.

The U.S. Air Force's Titan II ICBM was chosen for the Gemini Program. The Titan II GLV or Gemini-Titan would receive a number of modifications just as the previous launch vehicles required for the Mercury Program. Redundancy, an inertial guidance system, and structural modifications were needed to make the Titian II capable and suitable to launch humans into space. The Titian II's were therefore ordered and maintained by the Air Force. The Gemini Program tested capabilities needed for NASA's Apollo program to land a man on the moon and proved that American astronauts could leave their spacecraft, dock with another spacecraft and survive in space long enough to travel to the moon and back. Table 2 contains a listing of all Gemini Program missions. A few notable missions and American firsts are mentioned in the paragraphs below.

Rocket	Launched	Returned	Mission	Duration
Titan II	8-April-64	12-April-64	Gemini I	Unmanned
Titan II	19-Jan-65	19-Jan-65	Gemini II	Unmanned
Titan II	23-Mar-65	23-Mar-65	Gemini III	4 hrs, 52 min, 31 sec
Titan II	3-Jun-65	7-Jun-65	Gemini IV	4 days, 1 hr, 56 min, 12 sec
Titan II	21-Aug-65	29-Aug-65	Gemini V	7 days, 22 hrs, 55 min, 14 sec
Titan II	4-Dec-65	18-Dec-65	Gemini VII	13 days, 18 hrs, 35 min, 1 sec
Titan II	15-Dec-65	16-Dec-65	Gemini VI-A	1 day, 1 hr, 51 min, 24 sec
Titan II	16-Mar-66	17-Mar-66	Gemini VIII	10 hrs, 41 min, 26 sec
Titan II	3-Jun-66	6-Jun-66	Gemini IX-A	3 days, 21 hrs
Titan II	18-Jul-66	21-Jul-66	Gemini X	2 days, 22 hrs, 46 min, 39 sec
Titan II	12-Sep-66	15-Sep-66	Gemini XI	2 days, 23 hrs, 17 min, 8 sec
Titan II	11-Nov-66	15-Nov-66	Gemini XII	3 days, 22 hrs, 34 min, 31 sec

Table 2. Gemini Program Launches (after Grinter, *Gemini Missions*, 2000)

Unlike the Mercury Program that had 20 unmanned tests, the Gemini Program had only two, the first of which occurred on 08 April 1964. This made Gemini III the first manned Gemini mission. After a planned gap of nearly two years since the last American was in space, Gemini III lifted off on 23 March 1965 with Virgil Grissom and John Young on board and completed three orbits. During the Gemini IV mission, James McDivitt supported Edward White II as he completed the first extravehicular activity (EVA) by an American. White's EVA, or "space walk," lasted only 22 minutes, but it paved the way for even longer EVAs later in the Gemini Program. Frank Borman and James Lovell, Jr. set a new endurance record of 13.77 days in space during their Gemini VII mission, which satisfied the first objective of the Gemini Program. (Grinter, *The Gemini Flight Summary*, 2000)

An earlier planned Gemini VI mission was scrubbed because its Agena target booster for rendezvous and docking failed. This resulted in Gemini VII becoming the rendezvous target for the reworked Gemini VI-A mission. Gemini VI-A astronauts, Walter Schirra, Jr. and Thomas Stafford completed the first American spacecraft rendezvous with Gemini VII. After station keeping for over five hours at distances from

0.3 to 90 meters (1 to 295 ft), their mission was complete and ended after just over one day. (Grinter, *The Gemini Flight Summary*, 2000)

On 16 March 1966, Neil Armstrong and David Scott accomplished the first docking with another space vehicle, satisfying the second Gemini program objective. While Gemini VIII was docked to the unmanned Agena stage, a malfunction caused uncontrollable spinning of the spacecraft. This resulted in the first emergency landing of a manned U.S. space mission. The Gemini program met all of its goals with the exception of landing at a preselected point on land, which was cancelled in 1964. The last Gemini mission was Gemini XII. James Lovell, Jr. and Edwin Aldrin, Jr. rendezvoused and docked with a target Agena and kept station with it during an EVA. Aldrin set an EVA record at the time of 5 hours, 30 minutes for one space walk and two Stand-up EVAs (SEVA). A SEVA is where the astronaut is reliant on their spacesuit, but the astronaut does not fully leave the spacecraft. Photography, working just outside a hatch, taking experimental measurements, and jettisoning unneeded items are some typical uses for a SEVA. (Grinter, *The Gemini Flight Summary*, 2000; NASA, 2012)

The end of the Gemini Program resulted in the second planned break in U.S. manned space flight. The break was intended to be short. NASA was already launching the Saturn rockets that would be the launch vehicle for next NASA program, Apollo. The gap in manned space flights between Apollo and Gemini was planned for only three months, but instead took almost two years due to the catastrophic loss of three astronauts on Apollo 1. The Apollo 1 tragedy almost caused the demise of the entire Apollo program and set the schedule back almost 2 years.

3. The Apollo Program (1968–1972)

In November of 1959, NASA formed a study group to recommend upper-stage configurations for the future Saturn rocket. The committee was made up of the Department of Defense, Director of Defense Research and Engineering, personnel from NASA, Advanced Research Projects Agency, Army Ballistic Missile Agency, and the Air Force. This committee was known by a couple of different names, but is commonly referred to as the Silverstein Committee in honor of the committee chair Abe Silverstein. Many of the members were fighting for projects and programs as the roles for each organization were just starting to be defined. The outcome of this committee was a number of proposed rocket configurations. The most important outcomes from the Silverstein Committee for the Apollo program were the configurations that formed the basis for the Saturn I, Saturn IB and Saturn V. The Saturn I was the first dedicated heavy lift launch vehicle for the United States, which means it was designed to put payloads in orbit and not propel weapons toward enemy targets. Unlike the military rocket launch vehicles used for the Mercury and Gemini Programs that were converted from a Department of Defense role to a NASA mission, the Saturn Rockets were designed specifically for NASA's Apollo Program. Figure 2 illustrates the engine applications and numbers for the Saturn launch vehicles. Each subsequent version of the Saturn launch vehicle required a new and more powerful engine. (Bilstein, 2004)

The Saturn I vehicle had ten successful launches from 27 October 1961 until 30 July 1965. The major successes of the Saturn I were the launching of a number of Pegasus satellites and launch phase flight aerodynamics verification of the Apollo Command and Service Module. The Saturn I was replaced by the Saturn IB, when a more powerful 2nd Stage powered by the J-2 engine was available. The Saturn IB went on to successfully launch Apollo, Skylab crew missions and Apollo-Soyuz Test Project launches. The success of the J-2 engine on the Saturn IB lead to the Saturn V 2^{nd} Stage utilizing the J-2 engine in a five-engine cluster formation. The 2^{nd} stage of the Saturn IB was adapted for uses as the Saturn V 3^{rd} Stage. For the 1^{st} stage of the Saturn V, the F-1 engine was developed, which remains one of the most powerful rocket engines ever produced. Figure 2 shows this hardware commonality between the various Saturn launch vehicles configurations. (Bilstein, 2004)

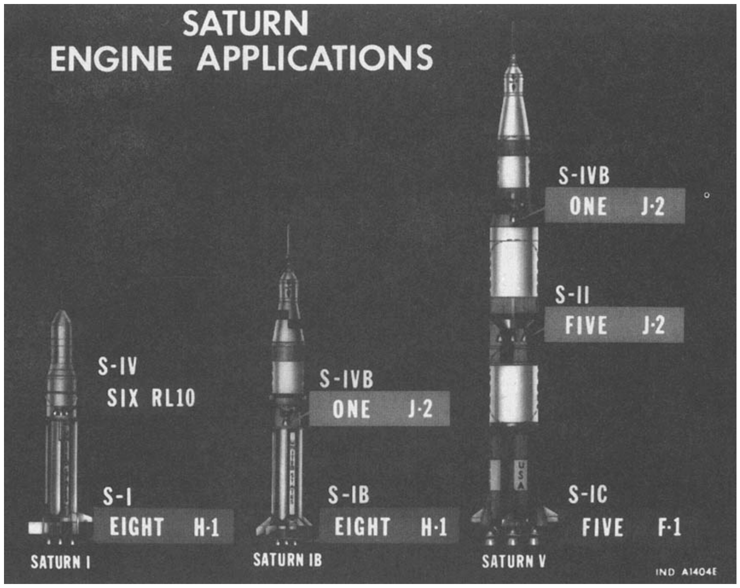

Figure 2. Saturn Launch Vehicle Engine Applications (from Bilstein, 2004)

The Apollo program built upon the lessons learned during the Mercury and Gemini programs. Apollo 1 was ready to launch after only three unmanned launches of the Saturn 1B. While the Apollo 1 rocket was still on the launch pad, tragedy struck. On 27 January 1967, a flash fire started in the Command Module during a planned ground test, killing astronauts Grissom, White, and Chaffee. A manned Apollo launch delay of almost 2 years took place to allow NASA to build a safer Block II version of the Command/Service Module (CSM). After three more unmanned launches, the first manned Apollo mission lifted off. Apollo 7 was the first manned Apollo mission and utilized the Saturn IB rocket, which by design did not provide enough power to leave Earth's orbit. Apollo 7 and 8 launched only the CSM. Apollo 8 was the first manned launch using the Saturn V rocket. It had the power to leave Earth's orbit and was the first mission to orbit the Moon. Apollo 9 and 10 tested the Lunar Module (LM) and CSM/LM operations. A size comparison of the Apollo CSM and LM is shown in Figure 3. Apollo 9 was an Earth orbit only test. Apollo 10 left Earth orbit and orbited the moon. Its LM came within 15,243 m (50,000 ft) of the lunar surface. It served as the dress rehearsal for Apollo 11 and the first lunar landing. (Grinter, *Apollo: The Moon Missions*, 2008)

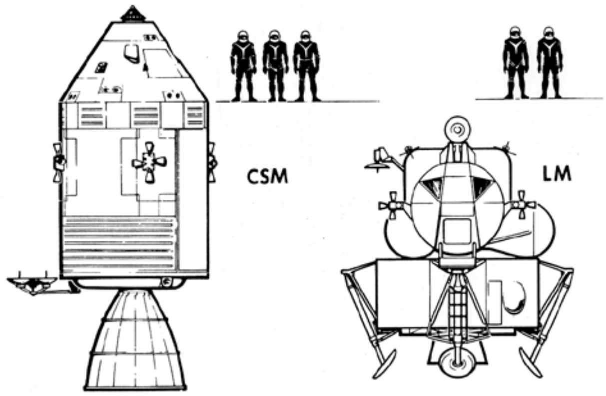

Figure 3. Apollo CSM and LM (from Teague, Project Apollo Diagrams, 2007)

On 20 July 1969, the Apollo 11 LM named Eagle landed on the moon. Astronaut Neil Armstrong was the first human to step onto the moon. Edwin (Buzz) Aldrin stepped on the moon just after him while Michael Collins remained in lunar orbit aboard the Apollo 11 CSM, Columbia. Only six more Apollo missions were subsequently launched. Apollo 13 had a failure that forced it to only fly by the moon and did not allow a moon landing. While the Apollo 13 mission was in route to the moon, “oxygen tank No. 2 blew up, causing the No. 1 tank also to fail. The Apollo 13 command module’s normal supply of electricity, light, and water was lost, and they were about 200,000 miles from Earth.” NASA and the Apollo 13 crew had to find a way to conserve air, water, power, and remove excess carbon dioxide. Both the CM and LM had lithium hydroxide canisters, which remove carbon dioxide from the spacecraft. The NASA team had to determine a way to make the square environmental system canisters from the CM connect with the round openings in the LM’s environmental system. The solution involved using plastic bags, cardboard, and tape that was on board Apollo 13. After Apollo 13, there were 4 more successful lunar landings (Grinter, *Apollo: The Moon Missions*, 2008).

Rocket	Launched	Returned	Mission	Duration
Saturn 1B	26-Feb-66	26-Feb-66	AS-201	Unmanned
Saturn 1B	25-Aug-66	25-Aug-66	AS-202	Unmanned
Saturn 1B	5-Jul-66	5-Jul-66	AS-203	Unmanned
Saturn 1B	N/A	N/A	Apollo 1	Cabin Fire, Crew Lost
Saturn V	9-Nov-67	9-Nov-67	Apollo 4	Unmanned
Saturn 1B	22-Jan-68	23-Jan-68	Apollo 5	Unmanned
Saturn V	4-Apr-68	4-Apr-68	Apollo 6	Unmanned
Saturn 1B	11-Oct-68	22-Oct-68	Apollo 7	10 days, 20 hrs
Saturn V	21-Dec-68	27-Dec-68	Apollo 8	06 days, 03 hrs
Saturn V	3-Mar-69	13-Mar-69	Apollo 9	10 days, 01 hr
Saturn V	18-May-69	26-May-69	Apollo 10	08 days, 03 min
Saturn V	16-Jul-69	24-Jul-69	Apollo 11	08 days, 03 hrs, 18 min
Saturn V	14-Nov-69	24-Nov-69	Apollo 12	10 days, 04 hrs, 36 min
Saturn V	11-Apr-70	17-Apr-70	Apollo 13	05 days, 22.9 hrs
Saturn V	31-Jan-71	9-Feb-71	Apollo 14	09 days
Saturn V	26-Jul-71	7-Aug-71	Apollo 15	12 days, 17 hrs, 12 min
Saturn V	16-Apr-72	27-Apr-72	Apollo 16	11 days, 01 hr, 51 min
Saturn V	7-Dec-72	19-Dec-72	Apollo 17	12 days, 13 hrs, 52 min

Table 3. Apollo Program Launches (after Grinter, *Apollo: The Moon Missions*, 2008)

The last manned mission to the moon was Apollo 17. During that mission, astronaut Eugene Cernan became the last person to stand on the moon. Astronaut Harrison Schmitt also walked on the moon during Apollo 17 while Ronald Evans supported the mission from lunar orbit in the CSM. The Apollo moon missions were canceled after only six lunar landings. This was earlier than had been planned. However, budget cuts and the desire to pursue the next launch vehicle, the Space Shuttle, caused three planned flights to be cancelled. A listing of all Apollo missions is given in Table 3. The early cancellation of the Apollo Program did not end U.S. manned space flight for long. Follow-on Apollo missions were planned with a destination other then the Moon. The United States returned to space less than five months later, this time using a Space Station known as Skylab. An international mission with the Soviet Union also took place between the last Apollo moon mission and the first Space Shuttle mission. (Grinter, Apollo: *The Moon Missions*, 2008; Williams, 2003)

4. Skylab and Apollo-Soyuz Test Programs (1973–1975)

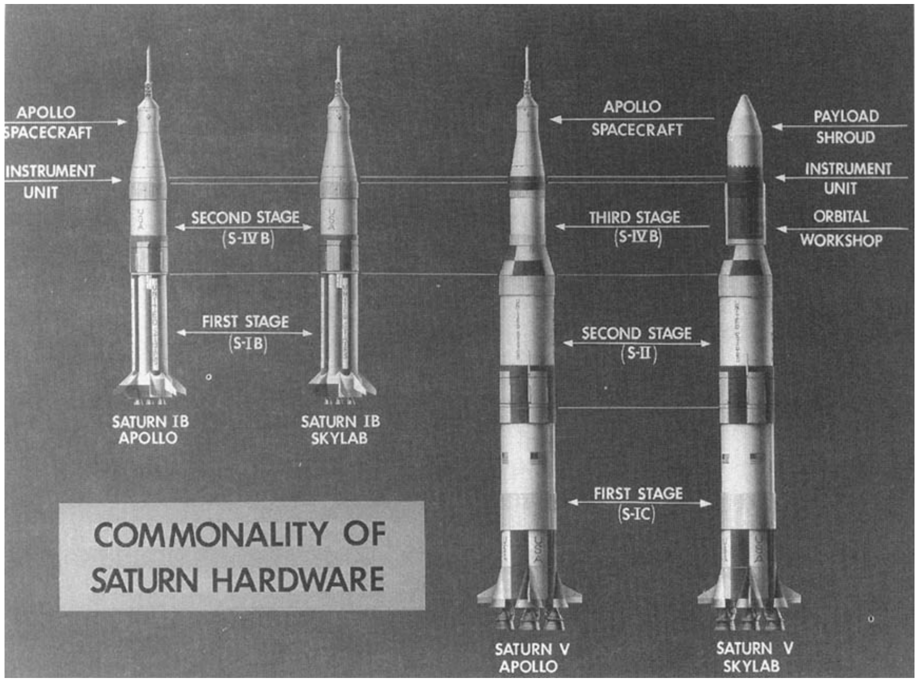

Figure 4. Commonality of Saturn Hardware (from Bilstein, 2004)

The Skylab missions built upon the Apollo program. The commonality of Saturn hardware is shown in Figure 4. An unused Saturn V rocket from the Apollo program was modified to launch the United States first Space Station known as Skylab. According to the NASA's Skylab website, the object of Skylab was twofold: "To prove that humans could live and work in space for extended periods, and to expand our knowledge of solar astronomy well beyond Earth-based observations." During the Skylab missions, both the man-hours in space and hours performing extravehicular activities (EVA) exceeded the combined totals of all previous Soviet and U.S. space flights. The three Skylab crews proved astronauts' ability to perform complex repair tasks both inside and EVAs outside Skylab. The capability to conduct longer manned missions was demonstrated by the Skylab Program with 28, 59 and 84-day mission. All of these activities paved the way for future NASA missions on the Space Shuttle and the International Space Station (ISS) (NASA, 2000; NASA, 2000).

After the three Skylab missions and some unmanned engineering tests, Skylab was positioned into a stable orbit/attitude and its systems were shut down. At the time, NASA expected Skylab would remain in orbit another eight to ten years. NASA had hoped Skylab would still be in orbit when its Space Shuttle Program would bring American astronauts back into space. The Space Shuttle would have been able to visit Skylab if this prediction of 8 to 10 years had been correct. However in 1979, it was determined Skylab's orbit was no longer stable due to higher than predicted solar activity. Therefore, Skylab had to be de-orbited earlier than planned. On 11 July 1979, Skylab re-entered Earth's atmosphere and impacted on Earth's surface in the Southeastern Indian Ocean and Western Australia. A listing of the Skylab missions is shown in Table 4 (NASA, 2000; NASA, 2000).

Rocket	**Launched**	**Returned**	**Mission**	**Duration**
Saturn V	14-May-73	11-Jul-79	Skylab 1	Skylab 2248.96 days
Saturn 1B	25-May-73	22-Jun-73	Skylab 2	28 days, 50 min
Saturn 1B	28-Jul-73	25-Sep-73	Skylab 3	59 days, 11 hrs
Saturn 1B	16-Nov-73	8-Feb-74	Skylab 4	84 days, 01 hrs
Saturn 1B	15-Jul-75	24-Jul-75	Apollo Soyuz	09 days, 07 hrs, 28 min

Table 4. Skylab and Apollo Soyuz Test Project Launches (after Grinter, *Skylab Flight Summary*, 2000; Grinter, *The Flight of Apollo Soyuz*, 2002)

The Apollo Soyuz Test Project was the first international manned space flight. According to the NASA's Apollo Soyuz Test Project website, "It was designed to test the compatibility of rendezvous and docking systems for American and Soviet spacecraft, to open the way for international space rescue as well as future joint manned flights." The United State's Apollo vehicle and the Soviet Soyuz vehicle both lifted off on 15 July 1975. The two spacecraft joined in space on 17 July at 11:10 a.m. (CDT) and separated on 19 July at 10:17 p.m. (CDT). A diagram of the two spacecraft is show in Figure 5. The Soviet Soyuz module landed in Kazakhstan on 21 July while the U.S. astronauts continued to do experiments in orbit until they eventually returned to Earth on 24 July 1975 (NASA History Division, 2005).

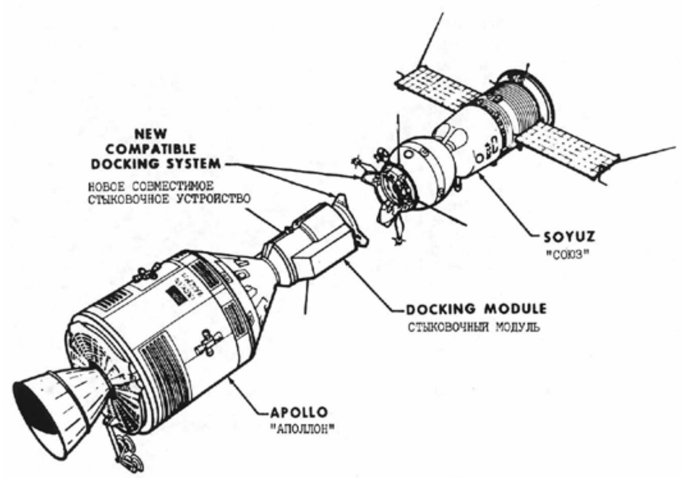

Figure 5. Apollo-Soyuz Diagram (from Teague, *Apollo-Soyuz Diagrams*, 2007)

The Apollo-Soyuz Test Project achieved the goal of increasing international cooperation on future joint manned flights includine Space Shuttle–Mir missions and ISS missions. The Apollo-Soyuz Test Project was the last launch of the Saturn family of launch vehicles. It was also the last U.S. manned space fight until the Space Shuttle launched in April of 1981. However, NASA already had Apollo's replacement in development. The Space Shuttle program had commenced before the Apollo program ended. The timeframe of 24 July 1975 until 12 April 1981 is the longest break in U.S. manned space flight to date. The break in manned space flight was needed to fund the Space Shuttle program in an era of reduced NASA budgets (Dun & Waring, 1999).

B. UNITED STATES SPACE TRANSPORTATION SYSTEM

After a gap of roughly 5½ years since the last Saturn launch, the United States returned Americans to space. The vehicle that took these American astronauts to space was the U.S. Space Transportation System (STS). This system was made up of three main components. The first was the Orbital Vehicle (OV). This served as the astronaut crew's home and held any equipment or supplies they needed in space. It also carried the payload to and from space. The OV is more commonly referred to as simply the Space Shuttle. When all three STS components were combined, they were also often referred to as the Space Shuttle or the name given to the specific orbiter in use. The OVs were designed to be capable of multiple space launches, which they all did repeatedly during their lifetimes. During the life of the Space Shuttle program, NASA built five operational Orbital Vehicles (OV) (NASA, 2011).

The second component was the huge External Tank (ET). The OV mounted to the outside of the ET. The ET supplied the fuel needed to power the Space Shuttle Main Engines (SSMEs) on the OV. The ET was the only component that was not reusable as it was destroyed when it re-entered the Earth's atmosphere. The ET was 153.8ft in length and 27.6ft in diameter. When empty the ET weighted approximately 66,000 pounds and was a maximum of 1,655,600 pounds when filled at launch (NASA, 2000).

The third and final Space Shuttle component was its two Solid Rocket Boosters (SRBs). Both SRBs attached to the External Tank, one on each side of the Space Shuttle Orbiter. Each SRB produced roughly 3,300,000 pounds of thrust at sea level and was 149.16 feet long and 12.17 feet in diameter. The SRBs were ignited three seconds after the OV's main engines started to insure that the OV main engines were functioning correctly, since once the SRBs were ignited they could not be stopped. The SRBs together provided 71.4 percent of the thrust of the entire system during lift-off. The SRBs separated from the ET relatively early in the mission (approximately two minutes after liftoff) and were also reusable on future launches. "The SRBs were the largest solid-propellant motors ever flown and the first designed for reuse" (NASA, 2000).

1. United States Space Shuttle Program (1981–2011)

The first operational Space Shuttle was Columbia (OV-102). Its first launch and thus the first launch of the Space Shuttle program took place on 12 April 1981. Challenger (OV-099) was the second operational Space Shuttle and first launched on 04 April 1983. Both of these vehicles were unfortunately destroyed, killing all onboard. Challenger was destroyed shortly after lift-off on 28 January 1986 due to an O-ring failure in the SRB that caused the ET to explode. Columbia was destroyed during re-entry on 01 February 2003 due to a hole in the reinforced carbon-carbon (RCC) leading edge of the left wing. The hole was caused by the impact of a piece of ET thermal foam insulation that occurred during ascent. NASA postponed future Space Shuttle launches for roughly 2½ years after each disaster, allowing them time to investigate and correct the failure causes. A graphical representation of all manned NASA space flights from Mercury through the Space Shuttle is given in Figure 6. It clearly shows these two gaps along with the gaps between each NASA manned space flight program (NASA, 2005; NASA, 2008; NASA, 2011).

The third vehicle made for NASA was Discovery (OV-103), and it first launched on 30 August 1984. The fourth orbiter produced was Atlantis (OV-104) and was first launched on 03 October 1985. After Challenger was destroyed, NASA was given approval to build another Orbital Vehicle. This vehicle was Endeavour (OV-105) and it was first launched on 07 May 1992. A complete listing of all Space Shuttle launches is given in Table 5 (NASA, 2011; NASA, 2012; NASA, 2008; NASA, 2008).

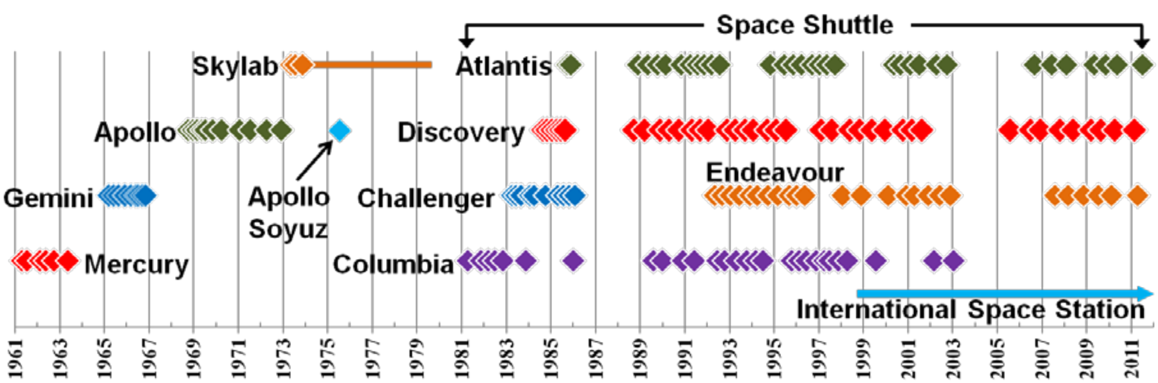

Figure 6. US Human Space Flight History (after NASA, 2011; Kauderer, 2011; Grinter, *Skylab Flight Summary*, 2000; Grinter, *The Flight of Apollo Soyuz*, 2002; Grinter, *Apollo: The Moon Missions*, 2008; Grinter, *Gemini Missions*, 2000; Grinter, *The Mercury Project - Flight Summary*, 2000)

Mission	Vehicle	Launched	Returned	Mission	Vehicle	Launched	Returned	Mission	Vehicle	Launched	Returned
STS-1	Columbia	12-Apr-81	14-Apr-81	STS-45	Atlantis	24-Mar-92	02-Apr-92	STS-91	Discovery	02-Jun-98	12-Jun-98
STS-2	Columbia	12-Nov-81	14-Nov-81	STS-49	Endeavour	07-May-92	16-May-92	STS-95	Discovery	29-Oct-98	07-Nov-98
STS-3	Columbia	22-Mar-82	30-Mar-82	STS-50	Columbia	25-Jun-92	09-Jul-92	STS-88	Endeavour	04-Dec-98	15-Dec-98
STS-4	Columbia	27-Jun-82	04-Jul-82	STS-46	Atlantis	31-Jul-92	08-Aug-92	STS-96	Discovery	27-May-99	06-Jun-99
STS-5	Columbia	11-Nov-82	16-Nov-82	STS-47	Endeavour	12-Sep-92	20-Sep-92	STS-93	Columbia	23-Jul-99	27-Jul-99
STS-6	Challenger	04-Apr-83	09-Apr-83	STS-52	Columbia	22-Oct-92	01-Nov-92	STS-103	Discovery	19-Dec-99	27-Dec-99
STS-7	Challenger	18-Jun-83	24-Jun-83	STS-53	Discovery	02-Dec-92	09-Dec-92	STS-99	Endeavour	11-Feb-00	22-Feb-00
STS-8	Challenger	30-Aug-83	05-Sep-83	STS-54	Endeavour	13-Jan-93	19-Jan-93	STS-101	Atlantis	19-May-00	29-May-00
STS-9	Columbia	28-Nov-83	08-Dec-83	STS-56	Discovery	08-Apr-93	17-Apr-93	STS-106	Atlantis	08-Sep-00	20-Sep-00
STS-41B	Challenger	03-Feb-84	11-Feb-84	STS-55	Columbia	26-Apr-93	06-May-93	STS-92	Discovery	11-Oct-00	24-Oct-00
STS-41C	Challenger	06-Apr-84	13-Apr-84	STS-57	Endeavour	21-Jun-93	01-Jul-93	STS-97	Endeavour	30-Nov-00	11-Dec-00
STS-41D	Discovery	30-Aug-84	05-Sep-84	STS-51	Discovery	12-Sep-93	22-Sep-93	STS-98	Atlantis	07-Feb-01	20-Feb-01
STS-41G	Challenger	05-Oct-84	13-Oct-84	STS-58	Columbia	18-Oct-93	01-Nov-93	STS-102	Discovery	08-Mar-01	21-Mar-01
STS-51A	Discovery	08-Nov-84	16-Nov-84	STS-61	Endeavour	02-Dec-93	13-Dec-93	STS-100	Endeavour	19-Apr-01	01-May-01
STS-51C	Discovery	24-Jan-85	27-Jan-85	STS-60	Discovery	03-Feb-94	11-Feb-94	STS-104	Atlantis	12-Jul-01	24-Jul-01
STS-51D	Discovery	12-Apr-85	19-Apr-85	STS-62	Columbia	04-Mar-94	18-Mar-94	STS-105	Discovery	10-Aug-01	22-Aug-01
STS-51B	Challenger	29-Apr-85	06-May-85	STS-59	Endeavour	09-Apr-94	20-Apr-94	STS-108	Endeavour	05-Dec-01	17-Dec-01
STS-51G	Discovery	17-Jun-85	24-Jun-85	STS-65	Columbia	08-Jul-94	23-Jul-94	STS-109	Columbia	01-Mar-02	12-Mar-02
STS-51F	Challenger	29-Jul-85	06-Aug-85	STS-64	Discovery	09-Sep-94	20-Sep-94	STS-110	Atlantis	08-Apr-02	19-Apr-02
STS-51I	Discovery	27-Aug-85	03-Sep-85	STS-68	Endeavour	30-Sep-94	11-Oct-94	STS-111	Endeavour	05-Jun-02	19-Jun-02
STS-51J	Atlantis	03-Oct-85	07-Oct-85	STS-66	Atlantis	03-Nov-94	14-Nov-94	STS-112	Atlantis	07-Oct-02	18-Oct-02
STS-61A	Challenger	30-Oct-85	06-Nov-85	STS-63	Discovery	03-Feb-95	11-Feb-95	STS-113	Endeavour	23-Nov-02	07-Dec-02
STS-61B	Atlantis	26-Nov-85	03-Dec-85	STS-67	Endeavour	02-Mar-95	18-Mar-95	STS-107	Columbia	16-Jan-03	Failure
STS-61C	Columbia	12-Jan-86	18-Jan-86	STS-71	Atlantis	27-Jun-95	07-Jul-95	STS-114	Discovery	26-Jul-05	09-Aug-05
STS-51L	Challenger	28-Jan-86	Failure	STS-70	Discovery	13-Jul-95	22-Jul-95	STS-121	Discovery	04-Jul-06	17-Jul-06
STS-26	Discovery	29-Sep-88	03-Oct-88	STS-69	Endeavour	07-Sep-95	18-Sep-95	STS-115	Atlantis	09-Sep-06	21-Sep-06
STS-27	Atlantis	02-Dec-88	06-Dec-88	STS-73	Columbia	20-Oct-95	05-Nov-95	STS-116	Discovery	09-Dec-06	22-Dec-06
STS-29	Discovery	13-Mar-89	18-Mar-89	STS-74	Atlantis	12-Nov-95	20-Nov-95	STS-117	Atlantis	08-Jun-07	22-Jun-07
STS-30	Atlantis	04-May-89	08-May-89	STS-72	Endeavour	11-Jan-96	20-Jan-96	STS-118	Endeavour	08-Aug-07	21-Aug-07
STS-28	Columbia	08-Aug-89	13-Aug-89	STS-75	Columbia	22-Feb-96	09-Mar-96	STS-120	Discovery	23-Oct-07	07-Nov-07
STS-34	Atlantis	18-Oct-89	23-Oct-89	STS-76	Atlantis	22-Mar-96	31-Mar-96	STS-122	Atlantis	07-Feb-08	20-Feb-08
STS-33	Discovery	22-Nov-89	27-Nov-89	STS-77	Endeavour	19-May-96	29-May-96	STS-123	Endeavour	11-Mar-08	26-Mar-08
STS-32	Columbia	09-Jan-90	20-Jan-90	STS-78	Columbia	20-Jun-96	07-Jul-96	STS-124	Discovery	31-May-08	14-Jun-08
STS-36	Atlantis	28-Feb-90	04-Mar-90	STS-79	Atlantis	16-Sep-96	26-Sep-96	STS-126	Endeavour	14-Nov-08	30-Nov-08
STS-31	Discovery	24-Apr-90	29-Apr-90	STS-80	Columbia	19-Nov-96	07-Dec-96	STS-119	Discovery	15-Mar-09	28-Mar-09
STS-41	Discovery	06-Oct-90	10-Oct-90	STS-81	Atlantis	12-Jan-97	22-Jan-97	STS-125	Atlantis	11-May-09	24-May-09
STS-38	Atlantis	15-Nov-90	20-Nov-90	STS-82	Discovery	11-Feb-97	21-Feb-97	STS-127	Endeavour	15-Jul-09	31-Jul-09
STS-35	Columbia	02-Dec-90	10-Dec-90	STS-83	Columbia	04-Apr-97	08-Apr-97	STS-128	Discovery	28-Aug-09	11-Sep-09
STS-37	Atlantis	05-Apr-91	11-Apr-91	STS-84	Atlantis	15-May-97	24-May-97	STS-129	Atlantis	16-Nov-09	27-Nov-09
STS-39	Discovery	28-Apr-91	06-May-91	STS-94	Columbia	01-Jul-97	17-Jul-97	STS-130	Endeavour	08-Feb-10	21-Feb-10
STS-40	Columbia	05-Jun-91	14-Jun-91	STS-85	Discovery	07-Aug-97	19-Aug-97	STS-131	Discovery	05-Apr-10	20-Apr-10
STS-43	Atlantis	02-Aug-91	11-Aug-91	STS-86	Atlantis	25-Sep-97	06-Oct-97	STS-132	Atlantis	14-May-10	26-May-10
STS-48	Discovery	12-Sep-91	18-Sep-91	STS-87	Columbia	19-Nov-97	05-Dec-97	STS-133	Discovery	24-Feb-11	09-Mar-11
STS-44	Atlantis	24-Nov-91	01-Dec-91	STS-89	Endeavour	22-Jan-98	31-Jan-98	STS-134	Endeavour	19-Apr-11	01-Jun-11
STS-42	Discovery	22-Jan-92	30-Jan-92	STS-90	Columbia	17-Apr-98	03-May-98	STS-135	Atlantis	08-Jul-11	21-Jul-11

Table 5. U.S. Space Shuttle Launches (after Kauderer, 2011; NASA, 2011)

After the fall of the Soviet Union, the U.S. and Russia began working together with more frequent efforts. The U.S. launched 10 missions to the Russian space station Mir. The first Space Shuttle-Mir mission was Space Shuttle Discovery mission STS-63. STS-63 lasted from 03 – 11 February 1995 and did not dock with Mir, but performed a fly-around maneuver with Mir, closing to within 37ft of eachother. The next nine Space Shuttle-Mir missions included successful dockings of the Space Shuttle and Mir. The first successful docking was with the Space Shuttle Atlantis and Mir as part of STS-71 from 27 June – 07 July 1995. The last Space Shuttle-Mir Mission was with the Space Shuttle Discovery during STS-91 from 02-12 June 1998. These nine Space Shuttle-Mir missions drove huge steps in international cooperation with the U.S. and Russia. The Space Shuttle-Mir missions were just Phase 1 of the plan to allow for Phase 2 to being, Phase 2 being what became the Inernational Space Station (NASA, 2004).

2. Capabilities

NASA's Space Shuttle program had been the United States' sole manned spaceflight platform for decades. Manned spaceflight is the first capability that usually comes to mind when discussing the U.S. Space Shuttle Program. However, the Space Shuttle brought more capabilities than just manned spaceflight to NASA and the United States. Besides carrying human cargo in its 2,325ft^3 (65.8m^3) crew compartment, the Space Shuttle also carried a large payload in the area directly behind them. This payload could be carried to and from space, which is a capability that no system previous has been able to do on the same scale (NASA, 2006).

a. Manned Space Flight Capability

Only two other nations have orbital manned Space flight capabilities. The first is Russia utilizing their Soyuz and most recently China with their Shenzhou spacecraft. With a few exceptions, the Space Shuttle has flown with a normal crew of between five and seven astronauts. However, the Space Shuttle has flown with as many as eight and as few as two astronauts. The first four Space Shuttle launches only had two astronauts, and the following two launches only had four astronauts. STS-61A had eight astronauts on the Space Shuttle Challenger. Space Shuttle Atlantis for STS-71 carried seven astronauts to the Russian space station Mir and carried eight back to Earth, bringing one Mir crewmember back with the Atlantis crew (NASA, 2011).

b. Heavy Space-Lift Capability

The Space Shuttle has taken into space more than half the mass of all payloads launched by all nations since Sputnik in 1957–an amount of 3,450,143 pounds (through STS-132). If the amount of material the Space Shuttle has taken into space isn't impressive enough, astronauts were also onboard each mission. The Space Shuttle carries cargo in a 15ft by 60ft cargo bay located directly behind the human crew compartment. Having the cargo payload on the same vehicle allows the human crew to utilize the Space Shuttle payload and utilize many of the Space Shuttle's unique capabilities. One well-known example of these unique capabilities is the repair work done on the Hubble Space Telescope. The Space Shuttle was able to carry replacement and servicing components aboard for repair and service of Hubble on three separate re-servicing missions. The Space Shuttle was also able to carry supplies and expansion modules with its crew to the International Space Station. Another unique capability of the Space Shuttle was the ability to carry science experiments to space and return with them to Earth. All of these unique missions would require at least two space vehicle launches to perform otherwise, one to launch the astronaut crew in orbit and another to deliver the payload to be utilized. A listing of the Space Shuttle's max payload capacity is shown in Table 6 (NASA, 2011).

Mission Type	Altitude & Inclination	Max Payload Capacity
Spacecraft Deployment Mission	204km (110 nmi), 28.45 deg	28,800 kg (63,500 lbm)
Science Platform	278 km (150 nmi), 28.45 deg	27,575 kg (60,800 lbm)
Spacecraft Servicing Mission	592 km (320 nmi), 28.45 deg	18,400 kg (40,600 lbm)
ISS Mission	407 km (220 nmi), 51.6 deg	18,300 kg (40,300 lbm)

Table 6. Space Shuttle Payload Capacities (after Isakowitz, Hopkins, & Hopkins, 2004)

As a comparison, the three of the last Space Shuttle Missions had the following payload masses. STS-133 (Discovery) had a total payload weight, not counting the middeck, of 36,514 pounds. STS-134 (Endeavour) had a total payload weight, not counting the middeck, of 29,323 pounds. STS-135 (Atlantis) had a total payload launch weight, not counting the middeck, of 31,015 pounds. STS-135 returned payload weight was expected to be 28,606 pounds. (NASA, 2011; NASA, 2011; NASA, 2011)

c. Payload Return to Earth (Down-Mass) Capability

Many space-lift systems can carry a payload into space, but relatively few can safely return items to Earth. The Space Shuttle brought back more than 97 percent of all mass returned to the Earth from orbit, a total of 225,574 pounds (though STS-132). Russia and China can return limited items back to Earth with their astronaut crew in their Soyuz and Shenzhou spacecraft, respectively. These spacecraft are designed primarily to launch and return humans back to the Earth. However, they could potentially be reconfigured into a return payload capacity, but this would only support a small mass when compared to the Space Shuttle. The United States Air Force X-37B and Space X Dragon have recently demonstrated a payload return capability, but do not currently offer the capability that the Space Shuttle did. They currently do not have the ability to have a human on board. Therefore they would need another spacecraft with an astronaut(s) on board to rendezvous with them in order for astronaut(s) to utilize or store a payload to return to Earth (NASA, 2011).

According to NASA publications for the Space Shuttle, "the abort landing weight constraints cannot exceed 50,500 lb. of allowable cargo on the so-called simple satellite deployment missions. For longer duration flights with attached payloads, the allowable cargo weight for end-of-mission or abort situations is limited to 25,000 lb." Given the previously stated maximum payload capabilities of the Space Shuttle, this means that the Space Shuttle could bring back to Earth pretty much anything that it could put up into space. This is a capability that the Space Shuttle preformed numerous times in it's history. As mentioned earlier STS-135 returned (estimated 28,606 pounds) just about the same amount of weight as it put into orbit (31,015 pounds). The Space Shuttle over its lifetime returned previously launched satellites, science experiments, International Space Station waste, and unneeded components (NASA, 1988; NASA, 2011).

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III. REPLACEMENT OPTIONS FOR THE SPACE SHUTTLE'S MANNED SPACE-LIFT CAPABILITY

A. CURRENT SYSTEMS

There have been and are many different plans from various countries to design and build a manned spacecraft program. However, many of these programs have been cancelled before they took flight. Some programs such as Spaceship One, built for Virgin Galactic, are sub-orbital and therefore unable to maintain a presence in outer space. Due to this, these suborbital spacecraft will not be mentioned further. There are three countries that currently have or had manned orbital space programs. They are the United States, Russia and China. With the retirement of the Space Shuttle, there are now only two active manned space flight programs, the Russian Soyuz and the Chinese Shenzhou. The sections below will discuss these current and other future options for the United States to launch astronauts into space and return them to Earth safely.

1. Russian Soyuz

The Russian Soyuz has been a workhorse for the Russian Space Federation since the Soviet Union era. The Soyuz program history began early in the Soviet space program. It was originally designed in the 1960's and first flew in 1967. There have been numerous modifications to the Soyuz spacecraft over the years. While there have been a number of different versions of the Soyuz spacecraft, they are all a part of the same heritage and family. There have been over 100 manned Soyuz launches. The Soyuz program is currently transitioning from the Soyuz TMA to the upgraded Soyuz TMA-M. (RIA Novosti, 2010; RIA Novosti, 2011)

a. Soyuz Design

The outside of the TMA and TMA-M are essentially the same. The major changes are on the inside. Thirty-six outdated items were replaced with 19 new-generation devices. The flight control, power supply and temperature systems were improved. The biggest change from the previous version is updating the old analog control system with a new onboard digital command and control system. As a result of these upgrades the weight of the Soyuz TMA-M was reduced, which allows it to carry an extra 70kg of cargo over the TMA version. The typical orbit along with some specifications and performances for the Soyuz-TMA are given in Table 7 (RIA Novosti, 2010; RIA Novosti, 2011).

Soyuz-TMA Specifications and Performances	
Design Life	14 days
Orbital Storage	200 days
Typical Orbit	407 km circular, 51.6° incl.
Length	6.98 m
Diameter of habitable modules	2.20 m
Maximum Diameter	2.72 m
Span	10.60 m
Habitable Volume	9.00 m^3
Launch Mass	6,800 kg
Upload Payload Mass	100 kg (for crew of 3)
	200 kg (for crew of 2)
Download Payload Mass	50 kg (for crew of 3)
	150 kg (for crew of 2)

Table 7. Soyuz TMA Specifications (after European Space Agency)

The Soyuz spacecraft is made of three modules, which are shown in Figure 7. The first module is the Orbital Module, which is pressurized and used by the crew during the orbital phase of their mission. The Orbital Module also houses the docking mechanism, the hatch, and the rendezvous antennas. These components are used when the spacecraft docks with the ISS or another space vehicle. The orbital module is detached during the descent phase and disintegrates when it re-enters Earth's atmosphere. (European Space Agency)

The next module is the Descent Module, which connects to the Orbital module on one end. The Descent Module is where up to three cosmonauts/astronauts sit during lift-off and re-entry, and therefore must contain all the required components to insure a safe re-entry. It contains an independent GNC system, seats, controls and displays, life support provisions, batteries, parachutes, and landing rockets. The Descent Module can also carry a small amount of payload to and from space or the International Space Station as shown in Table 7. (European Space Agency)

While humans can enter the first two modules, the last module is uninhabitable. The Instrumentation and Service Module is the last module and connects to the Descent Module. Like the Orbital Module, the Service Module is discarded before the descent phase and burns up in the Earth's atmosphere. The Service Module houses the oxygen, life support, power, communications, thermal control, and propulsions systems. The solar arrays for the Soyuz are also mounted to the outside of the Service Module. (European Space Agency)

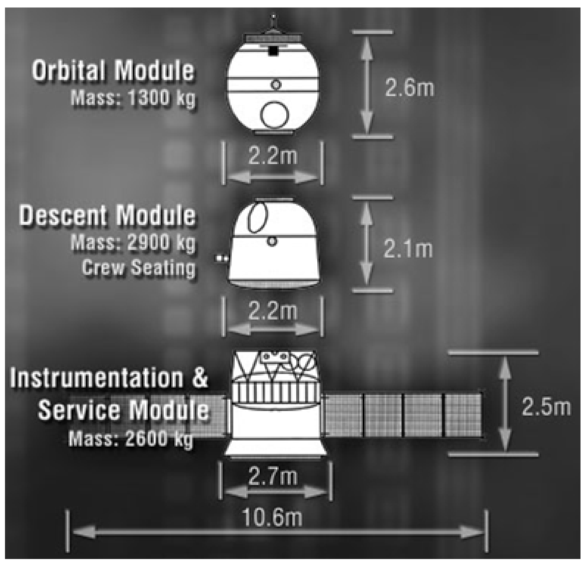

Figure 7. Diagram of Soyuz TMA (from NASA, 2010)

b. Soyuz and Space Shuttle Comparison.

With the United States' Space Shuttle fleet now retired, the Russian Soyuz is the only spacecraft that can carry humans to and from the International Space Station (ISS). While the Soyuz carries humans to the ISS very well, it does not have the same capacity or all the capabilities that the Space Shuttle provided. A simple scale comparison of the Space Shuttle and Soyuz is shown in Figure 8. As the scale comparison shows, Soyuz is much smaller than the Space Shuttle. In fact roughly two Soyuz TMA spacecraft could fit inside the cargo bay of the Space Shuttle (European Space Agency; NASA, 2011).

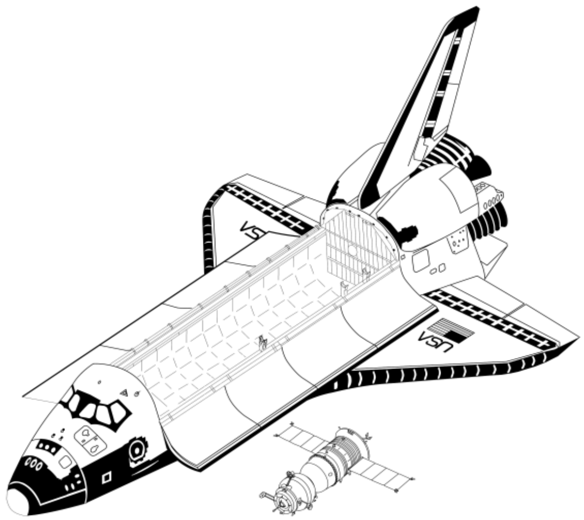

Figure 8. Scale Comparison of Space Shuttle and Soyuz (from Portree, 1995)

The Space Shuttle normally carried between six and seven astronauts at a time, but had carried as few as two and as many as eight at a time. Soyuz can only carry up to three astronauts/cosmonauts at one time. This means it would take at least two Soyuz launches to carry the same amount of astronauts as one Space Shuttle launch. While it may not be a requirement for every mission to have over three astronauts, there are times where the mission might be complex enough to require it. Each member of a mission has been trained to perform certain tasks or has specific talents and knowledge. Adding members to a mission allows for more possible tasks that can be performed. To have the same capability as the Space Shuttle, it would require at least two Soyuz spacecraft launches and at least one additional cargo launch vehicle to deliver the same human and non-human capability to space. Having the astronauts and cargo payload together in space is important for scientific missions or other missions that require humans and a non-human payload, such as a Hubble Space Telescope repair mission or assembly of a space station. (European Space Agency; NASA, 2011)

Since the United States is not the government in charge of launching the Soyuz, it is completely dependent on the launching nation, Russia. While the relationship between Russia and the United States is generally considered good, Russia is free to use Soyuz launch humans and payloads from nations who are opposed to the United States. If Russia favors another nation, company or individual more than the United States, then they could launch for that entity instead of or before the United States. By 2020, the United States, Russia, Europe, Canada and Japan are expected to have invested more than $100 billion in the ISS. NASA's ISS costs alone are estimated to be more than $3 billion annually through 2020. Given the international investment in the ISS, it would be hard for Russia to accept the worldwide political toll they would suffer if they neglected their role in fulfilling the manned space flight missions to the ISS for any of nations invested in ISS. While the Soyuz spacecraft may not have the same launch capabilities as the Space Shuttle in terms of cargo and crew size, it does a very good job of satisfying the mission of launching and returning the ISS crew. The fact that it is currently the only option for this mission does affect its ability to satisfy this mission (Svitak, 2012).

2. Chinese Shenzhou

China is the third and most recent country to place a human into space. The Chinese Shenzhou program and spacecraft is in its infancy. There have been nine launches of the Shenzhou spacecraft through 2012, and only four of them have been manned. Shenzhou 1, 2, 3, 4, and 8 were all unmanned. Shenzhou 5, 6, 7, and 9 were manned and carried between one and three Chinese astronauts into space. A listing of the Shenzhou launches to date is shown in Table 8 (NASA, 2012).

Shenzhou means “Divine Vessel” in Chinese. The Shenzhou spacecraft is based on the three-seat Russian Soyuz spacecraft. Since it is not just a copy of the Soyuz, the Shenzhou its component are more up to date. The budget for China's space program was a closely held secret. The Chinese government announced that it had spent $2.18 billion (in U.S Dollars) up to the point of the Shenzhou 5 launch. The Chinese used the Long March 2F rocket to launch the Shenzhou spacecraft into orbit from Jiuquan in northwest China. The Shenzhou spacecraft is slightly larger in size than the Russian Soyuz at 2.8 m diameter and 9.5 m high. Like the Soyuz it has three sections. The Shenzou has a retrievable crew module, a service module for storing fuel and equipment, and an orbiter to continue on after the release of the crew module. After the crew module re-enters Earth’s atmosphere, it will make a soft landing on the grasslands of Inner Mongolia using parachutes (NASA, 2011; NASA, 2011).

Spacecraft Name	**Launch Date**
Shenzhou	November 19, 1999
Shenzhou 2	January 9, 2001
Shenzhou 3	March 25, 2002
Shenzhou 4	December 29, 2002
Shenzhou 5	October 15, 2003
Shenzhou 6	October 12, 2005
Shenzhou 7	September 25, 2008
Shenzhou 8	October 31, 2011
Shenzhou 9	June 16, 2012

Table 8. List of Shenzhou Launches (after NASA, 2012)

Shenzhou 5, which was manned by Lt. Col. Yang Liwei, orbited the Earth for nearly 21.5 hours and made a total of 14 orbits. Shenzhou 6 carried two Chinese astronauts into orbit around for about five days. The orbiter module, which remained in orbit, continued to do autonomous scientific research and transmitted data to receiving stations on Earth. Shenzhou 7 carried three astronauts for a three-day mission in a return capsule. One of the three astronauts made a brief spacewalk during the flight. This was mainly to test the Chinese space suit called Feitian, after the goddess who could fly. The Shenzhou 9 lasted roughly 13 day and had the primary mission of docking with China's first space lab (Tiangong-1). It posted a number of firsts for China. It was the first flight of a female Chinese astronaut, the first manned dockings of two Chinese spacecraft, China’s first long-duration mission, and the first Chinese crew to live aboard a permanently orbiting module, Tiangong-1 (Amos, 2012; NASA, 2011; NASA, 2011; NASA, 2011).

Due to secrecy by the People's Republic of China (PRC) and the relative newness of the program, many details of the Shenzhou spacecraft are not published or available. Since the Shenzhou is very similar to the Russian Soyuz, its suitability as a Space Shuttle replacement is roughly the same. The Shenzhou can only hold about half as many astronauts as the Space Shuttle and can't carry a sizeable payload with it. As with the Soyuz, this would result in requiring multiple launches to do what the Space Shuttle could accomplish with one.

While the United States has significant business exchange with China, the relationship between the two nations has been strained at times. For example, if China wanted to make a point about their dislike for the U.S.'s stance on Taiwan, it could deny the U.S. access to its Shenzhou spacecraft. This of course assumes that the U.S. ever becomes interested in or needs to utilize the Chinese Shenzhou for some reason. Currently the U.S. has not officially expressed any interested in utilizing the Shenzou. Beyond this, the Shenzhou is a relatively unproven system. It has had only four manned flights in the nine years since its first manned space flight. At this rate China has not proven that it can support the frequency and number of launches that the United States would require to maintain a presence in space on the ISS or other scientific mission the Space Shuttle performed. After taking into account all these things, the Shenzhou spacecraft is not a suitable substitute for the U.S. Space Shuttle, even if the United States government considered partnering with China to use Shenzhou.

B. FUTURE U.S. PROGRAMS

According to NASA Administrator Charles Bolden in a recent press release, "We are committed to human exploration beyond low-Earth orbit and look forward to developing the next generation of systems to take us there. The NASA Authorization Act of 2010 lays out a clear path forward for us by handing off transportation to the International Space Station to our private sector partners, so we can focus on deep space exploration. As we aggressively continue our work on a heavy lift launch vehicle, we are moving forward with an existing contract to keep development of our new crew vehicle on track." (NASA Newsroom, 2011)

NASA is focusing on taking American astronauts beyond low Earth orbit. NASA Administrator Charles Bolden said in a July 2011 news conference that, "I made a decision to base the new multi-purpose crew vehicle, or MPCV–our deep space crew module -- on the original work we've done on the Orion capsule. We're nearing a decision on the heavy lift rocket, the Space Launch System, or SLS, and will announce that soon." Any such program would also be beyond the missions the Space Shuttle was designed for. The Space Shuttle was only designed for Low Earth Orbit (LEO) missions. Therefore SLS and any manned spacecraft designed for missions beyond LEO are beyond the scope of this thesis. (NASA Newsroom, 2011)

The United States has placed its future for launching American astronauts into low Earth orbit in the hands of commercial companies. Instead of developing its own program, NASA is planning to contract with commercial companies for its low Earth orbit manned space flight missions. This commercial option is under NASA's Commercial Crew Program (CCP). There have been three rounds of competition so far in the program, with each round the designs becoming more refined and detailed. The first round was to develop design concepts. The second round ended with preliminary designs. The third round will develop the designs to the point they are ready for production. The first two rounds of competition were known as Commercial Crew Development - Round 1 and 2 (CCDev1 and CCDev2). The third round is called Commercial Crew Integrated Capability (CCiCap).

1. Commercial Crew Integrated Capability (CCiCap)

As stated in the NASA press release announcing the contractors selected for Commercial Crew Integrated Capability (CCiCap), NASA "announced new agreements with three American commercial companies to design and develop the next generation of U.S. human space flight capabilities, enabling a launch of astronauts from U.S. soil in the next five years. Advances made by these companies under newly signed Space Act Agreements through the agency's Commercial Crew Integrated Capability (CCiCap) initiative are intended to ultimately lead to the availability of commercial human space flight services for government and commercial customers.

CCiCap partners are:

-- Sierra Nevada Corporation (SNC), Louisville, Colo., $212.5 million

-- Space Exploration Technologies (SpaceX), Hawthorne, Calif., $440 million

-- The Boeing Company, Houston, $460 million" (Thomas & Perrotto, 2012)

According to the selection authority for Commercial Crew Integrated Capabilities (CCiCap), "I believe it is in NASA's interest to include three companies in the section because it adds robustness to the overall portfolio. This portfolio provides for a diversity of spacecraft designs (capsule and winged lifting body) as well as capturing the proposal that provides the earliest crewed demonstration flight under a credible schedule at the lowest development cost (SpaceX), and the proposal that represents the highest Level of Effectiveness and Confidence ratings on the technical approach (Boeing). Carrying a third company would keep competition even if one company needed to drop out. However, I do not have the funding to include all three companies in the portfolio at the levels of NASA contribution they have proposed. SNC has the most significant amount of risk reduction and technology development work to do before reaching CDR, and I would like to see what kind of progress SNC can make on increasing the maturity of some of its key technologies and reducing some of its key risks to increase my confidence in its ability to reach CDR before providing them with additional funding. For this reason, I decided that SNC would receive a significantly reduced award." (Gerstenmaier, 2012)

This means the two companies NASA has confidence to proceeding to the Critical Design Review (CDR) are SpaceX and Boeing. Sierra Nevada Corporation (SNC) is being added to provide competition if one of these two companies falter and to provide some diversity in design.

a. Dragon Spacecraft

The Dragon spacecraft is being developed by Space Exploration Technologies Corporation, which is most often known as SpaceX. The Dragon spacecraft is a capsule design and will launch on SpaceX's Falcon 9 rocket. This is a departure from the other CCiCap designs which all plan to at least initially launch on a man-rated Atlas V. SpaceX will have a crew, cargo, and lab version of their Dragon capsule. The cargo version will deliver supplies to the International Space Station under a separate contract with NASA. There have been four successful flights of this version, which took place on the 09 December 2010, 22 May 2012, 08 October 2012, and 01 Mach 2013. This first launch was the first privately funded company to successfully launch, orbit and recover a spacecraft. The second launch was the first commercial mission to the International Space Station. As a part of SpaceX Commercial Resupply Services (CRS) contract with NASA, the third and fourth launches were also to the ISS as CRS-1 and CRS-2, respectively. There is also a lab version (DragonLab) planned for non-crew and non-ISS resupply missions that need cargo or experiments put into orbit. Any items in the capsule portion of Dragon spacecraft will also be returned to Earth. (NASA & SpaceX, 2012; Perrotto & Byerly, 2012; Space Exploration Technologies Corp, 2012; Space Exploration Technologies Corp, 2013)

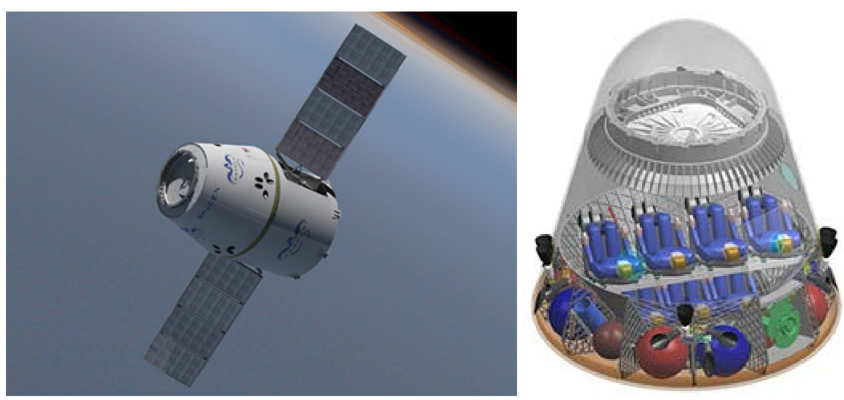

Figure 9. Rendering of Dragon Spacecraft and Crew Configuration (from Space Exploration Technologies Corp, 2010)

One large advantage for SpaceX and the Dragon Capsule has is that the launch vehicle, the Falcon 9, has already been designed to have a human-rated capability. While the other CCiCap systems plan to use a human-rated Atlas V, SpaceX already has a launch vehicle that was designed to be capable of human use. The Atlas V will have to be modified or retrofitted, as it was not designed for humans. This is a risk to the other systems, since the Atlas V may not be ready when they need it. This means, SpaceX could potentially have a serious advantage (Shanklin, 2009).

Another advantage for SpaceX is that their Dragon crew capsule is based on their Dragon cargo capsule. According to SpaceX's website, "to ensure a rapid transition from cargo to crew capability, the cargo and crew configurations of Dragon are almost identical, with the exception of the crew escape system, the life support system and onboard controls that allow the crew to take over control from the flight computer when needed." This means SpaceX is able to build on a proven design that has already flown and will continue to fly in space during the development of the crew capsule through CCiCap (NASA & SpaceX, 2012; Space Exploration Technologies Corp, 2012).

The crew version of the Dragon capsule is designed to hold seven astronauts and take them to and from the ISS. Beyond the ISS, SpaceX would also be able to launch to other missions in LEO, such as a Bigelow Aerospace space habitat. These non-ISS missions could be for other NASA, other U.S. government agencies, other nations, or for commercial use. Since there is limited room inside the Dragon crew capsule, these missions for Dragon would likely only be used as a transportation service from point to point. The Dragon cargo spacecraft does have the capability to produce power through its solar arrays. With properly sized solar arrays, there is a potential for longer missions in LEO orbits. However, they would likely be limited to historical Gemini program lengths due to the passengers' limited mobility. Long duration missions, such as those the Space Shuttle performed, would require more space and support functions than the Dragon crew capsule is planned to provide. The Dragon capsule should provide a good substitute for the Space Shuttle short duration manned space flight missions (NASA & SpaceX, 2012; Space Exploration Technologies Corp, 2012).

b. CST-100

The CST-100 (Crew Transportation System) is the crew launch capsule being developed by Boeing for Commercial Crew Integrated Capability (CCiCap). Boeing's designs objectives for CST-100 are to utilized simple systems and proven components. "These include utilizing the APAS (Androgynous Peripheral Attach System) docking system (on ISS), Orbital Express demonstrated AR&D (Automated Rendezvous & Docking), Apollo heritage parachute system, abort system using existing components, BLA (Boeing Lightweight Ablator) from other programs, Delta-based spin formed structures, and airbag landing system from CEV/Orion." The goal is to utilize proven components that are safe and reliable. By utilizing proven heritage components, hardware, and software, Boeing hopes to keep development and schedule risk low while reducing cots. CST-100 is designed to be compatible with a number of launch vehicles. However, Boeing plans to initially utilize the human-rated Atlas V (Burghardt, 2011).

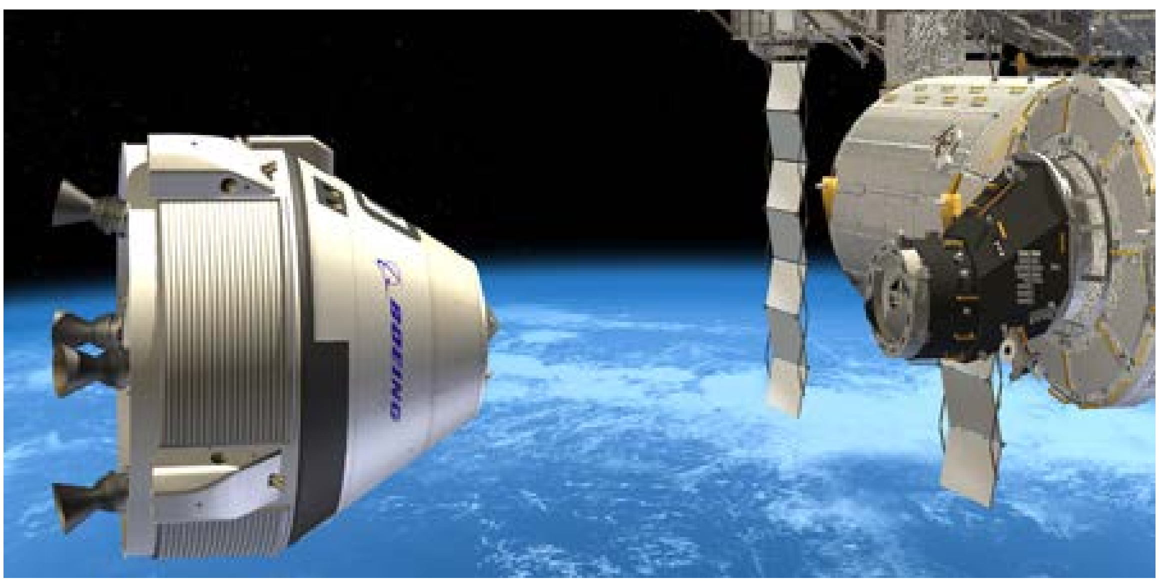

Figure 10. Rendering of Boeing CST-100 Docking with ISS (from Burghardt, 2011)

According to Boeing's paper on CST-100 presented at the AIAA Space 2011 conference, "With Bigelow Aerospace and NASA as launch customers, Boeing has designed the CST-100 to meet the needs of multiple markets." This agreement is something unique to Boeing and CST-100. Boeing plans missions to ISS and Bigelow Aerospace's expandable space station modules. CST-100 is designed to carry a maximum of seven crewmembers. This will allow Boeing the flexibility to support a verity of missions and costumers. A key feature of CST-100 is their Pusher Launch Abort System. This provides the crew safety on a range of launch vehicles in case of emergency. "The CST-100 will transport crew to LEO destinations of 250 nm altitude at 51.6° inclination for ISS, and to 225 nm at 35° inclination for the Bigelow Space Complex. The CST-100 can operate autonomously for up to 60 hours of free flight, and is designed for a Day One rendezvous with a Day Two backup opportunity. The vehicle can stay docked to a host complex for up to 210 days while provided with one kW of keep-alive power. The CST-100 utilizes Airborne Systems parachutes as an aerodynamic decelerator to accommodate land landing on ILC Dover airbags. System Capability is provided for contingency water landings as well." (Reiley, Burghardt, Wood, Ingham, & Lembeck, 2011)

Boeing has a proven track record designing many successful space launch vehicles and satellites. Boeing was one of two principle stakeholders of the United Space Alliance for the Space Shuttle operations and is a prime contractor to NASA for the ISS. Boeing has designed and built many different models of the Delta launch vehicles. Therefore, Boeing has firsthand knowledge of what it takes to design, test, build, and launch manned and unmanned object into space. In the human space flight business, safety and dependability are critical. Therefore, many in the space industry depend on contractors with a proven track record and pedigree. While not a guarantee of success, no other contractor in CCiCap has more experience than Boeing. NASA believes Boeing history sets it up well to be able to deliver CST-100 to meet NASA's commercial manned space flight needs. CST-100 should provide the manned space flight capability the Space Shuttle did for trips to and from the ISS or other LEO space stations.

c. Dream Chaser

Dream Chaser is a commercial space transportation system proposed by Sierra Nevada Corporation for NASA's Commercial Crew Integrated Capability

(CCiCap) program. Dream Chaser is designed to carry a maximum of seven crewmembers. It is also the only proposal that is a lifting-body spacecraft like the Space Shuttle and not a capsule like Apollo, Soyuz, or the other CCiCap designs. It is based on the NASA HL-20 design and will be launched on an Atlas V. Dream Chaser will land on a runway and be re-useable like the Space Shuttle. The landing will be on a conventional runway and as a result it will be a low-impact horizontal landing. Other CCiCap designs will land where their trajectory takes them. The Dream Chaser will have a cross range capability that will allow it to modify or change its landing location. This is important if an abort or a need arises to change its landing site. The cross range capability will also allow Dream Chaser more re-entry opportunities (Norris, 2011; Sierra Nevada Corporation Space Systems; Sierra Nevada Corporation, 2011).

Figure 11. Rendering of Dream Chaser Docking with ISS (from Sierra Nevada Company, 2011)

Sierra Nevada's Dream Chaser is based on largely proven designs. The spacecraft design is derived from NASA's HL-20 crew vehicle. The HL-20 has years of development, analysis, and wind tunnel testing by the Langley Research Center. Sierra

Nevada worked on the Spaceship One and Spaceship Two hybrid rocket motors. The Dream Chaser's on-board propulsion system is also based on this proven design heritage. Sierra Nevada's hybrid rocket propulsion technology has been developed for over 10 years and over 300 firings. This hybrid rocket technology uses safe, non-toxic, storable, and most importantly human flight-tested propellant (Norris, 2011; Sierra Nevada Corporation, 2011).

Despite all this, Sierra Nevada has a number of technical and design hurdles to overcome. Some of them were alluded to in the CCiCap selection statement. Sierra Nevada also has a financial issue as well. With less than half the funding from NASA as Boeing and SpaceX, a large amount of additional financing from another source will be required to develop the technology enough to be successful. Unless Sierra Nevada shows good progress addressing the NASA identified deficiencies, they are unlikely to receive additional NASA funding. Boeing or SpaceX would likely require a set back or not mature as expected for Sierra Nevada to receive more NASA funding. Without more NASA funding, it is unlikely that Dream Chaser will become a reality. However, Dream Chaser has an advantage being the only CCiCap spacecraft utilizing a lifting-body design. If produced, it would serve as a good replacement to the Space Shuttle's manned missions to the ISS or other Low Earth Orbit (LEO) space stations.

2. Non-United States Options

Few other space programs have come to fruition. Current non-US human space flight systems were discussed earlier. Other countries do have plans for future human space flight systems. Two examples are the CSTS (Crew Space Transportation System) and ACTS (Advanced Crew Transportation System). The CSTS was a joint project with the European Space Agency (ESA) and the Russian Federal Space Agency. In 2009, Europe and ESA decided to develop a manned version of its Automated Transfer Vehicle (ATV). Russia decided to continue with a version of the CSTS original design and renamed it the PPTS (Prospective Piloted Transport System). ESA has decided upon a similar concept to SpaceX's Dagon Capsule. ESA plans to adapt and upgrade its ATV spacecraft for safe operation for crew usage. As mentioned earlier SpaceX plans to take its Dragon Capsule, which they first plan to use for resupply mission to ISS, then use for manned mission to ISS later. (BBC News, 2009; Zak, Prospective Piloted Transport System, 2011; Zak, Russia to unveil spaceship plans, 2009)

With the current global economic downturn it is unclear if any future non-US systems will actually operate. As an example, the United States cancelled its Constellation program, which likely would have survived in better economic times. This same economic pressure will likely cause other nations and organization to delay or cancel their future human space flight programs. It is very unlikely that any future non-US systems will be ready before NASA selects and launches on at least one of the CCDev contractor's manned space flight vehicles, previously discussed.

IV. REPLACEMENT OPTIONS FOR THE SPACE SHUTTLE'S HEAVY SPACE-LIFT CAPABILITY

Launch Vehicle		Orbit Altitude			Max Payload	
Name	**Origin**	**200km LEO**	**400km ISS**	**GTO**	**Length**	**Diameter**
Space Shuttle	U.S.	28,800 kg	18,300 kg		18.288m	4.572m
Current Launch Vehicles						
Falcon 9	U.S.	13,150 kg		4,850 kg	11.4m	4.6m
Proton	Russian	23,000 kg		6,920 kg	10.342m	3.810m
Delta M+(5,4)	U.S.		13,360 kg	7,020 kg	15.995m	4.572m
H-IIB	Japan		16,500 kg	8,000 kg	15m*	5.1m*
Atlas 551	U.S.		18,510 kg	8,900 kg	16.475m	4.572m
Ariane 5	Europe	21,000 kg	19,000 kg	9,500 kg	15.589m	4.570m
Delta Heavy	U.S.		22,560 kg	12,980 kg	16.474m	4.572m
Future Launch Vehicles						
Angara A5	Russian	24,500 kg		7,500 kg	Unknown	Unknown
Angara A7	Russian	35,000 kg		12,500 kg	Unknown	Unknown
Atlas HLV	U.S.		29,400 kg	13,000 kg	16.475m	4.572m
Long March 5	China	25,000 kg		14,000 kg	Unknown	5m*
Falcon Heavy	U.S.	53,000 kg		12,000 kg	11.4m	4.6m
*** Max Payload will be less. External Fairing Dimensions only listed in source documents**						

Table 9. Launch Systems Payload Capacities (after Arianespace, 2011; CASC; International Launch Services, 2009; Isakowitz, Hopkins, & Hopkins, 2004; JAXA; JAXA, 2009; Khrunichev State Research and Production Space Center; Nimura, Goto, Kondo, Egawa, Nakamura, & Arita, 2008; Perrett, *Longer Marches*, 2010; SpaceX, 2012; United Launch Alliance, 2007; United Launch Alliance, 2010)

No system that currently exists or is currently projected will possess the Space Shuttle capability to have astronauts manually deploy or service satellites. This unique capability is not needed to launch large objects into space. There are a number of options available to the United States, other nations, and private companies that can launch assets into space. The United States Space Shuttle payload capabilities were given earlier in Table 6 and repeated in Table 9. The users' guide or stated capabilities for each launch system provided different launch parameters. The capabilities of each system are categorized in the listed columns. For example, the Delta IV Heavy and Space Shuttle had launch capabilities to put an object into a 400km class of orbit, but they were at different inclinations, 28.5° and 51.6°, respectively (United Launch Alliance, 2007).

The United States government has historically launched their payloads utilizing domestic launch systems. Private American companies have been selecting domestic and non-domestic launch vehicles to put their payloads into space. Due to the cost and availability of the Space Shuttle, few non-scientific or ISS payloads were launched by the Space Shuttle, especially towards the end of the program. Given that the United States prefers domestic launch vehicles for its military, national asset, and government funded payloads, it is unlikely that will change for future launch systems. Therefore, from a United States government payload prospective domestic launch systems are almost a firm requirement for any Space Shuttle space launch replacement. Thus, limited discussion of non-US launch systems will be made in this thesis due to the fact they are capable options at least for private industry.

A. CURRENT SYSTEMS

1. Delta IV Heavy

The Boeing designed Delta IV Heavy is the closest launch vehicle in the United States to the Space Shuttle's launch capability. Unlike its commercial launches, the Delta IV is launched for U.S. government launches as a part of the Boeing and Lockheed's joint venture, United Launch Alliance. The Delta IV rockets have been launched from the main U.S. ranges, Cape Canaveral Air Force Station in Florida and Vandenberg Air Force Base in California. While the Delta IV Heavy is the biggest launch vehicle currently in the United States, there are other smaller versions of the Delta IV available. The core Delta IV is the Delta M or Delta Medium. This consists of just the main liquid engine, tanks, upper stage, and payload with fairing. To increase the amount of payload the Delta IV can put into orbit, two or four solid rocket motors can be added to the side of the main booster. If even more mass needs to be placed into orbit, then three for the main boosters can be strapped side by side to form the base of the Delta IV Heavy. These configurations are shown in Figure 12 (United Launch Alliance, 2010; United Launch Alliance, 2007).

The largest Delta IV Medium version is the Delta M+(5,4), with a 5m fairing and four strap-on solid rockets. While it comes relatively close to the Space Shuttle, the Delta IV Heavy is the largest launch vehicle currently available inside the United States. It can launch more mass into orbit than the retired Space Shuttle. The capabilities of both the Delta IV Heavy and Delta M+(5,4) are given in Table 9. The values given for the Delta vehicles were at the following orbits: Geosynchronous transfer orbit (GTO) of 35,786 x 185 km at 27° inclination and Low-Earth Orbit (LEO) of 407km at 28.5° inclination with the Government Fairing (United Launch Alliance, 2010; United Launch Alliance, 2007).

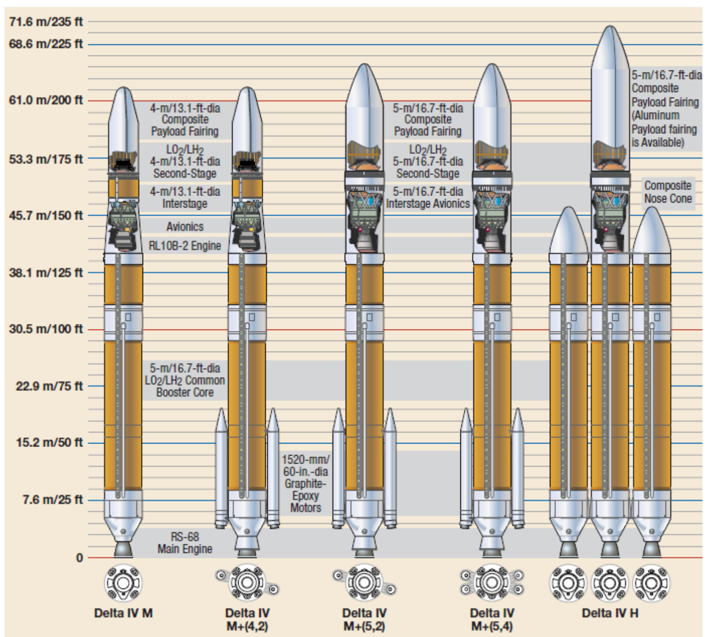

Figure 12. Delta IV Configurations (from United Launch Alliance, 2007)

The Delta IV Heavy is a suitable replacement for the Space Shuttle in terms of payload launch mass capability but is over 1.8m shorter in payload length. Most payloads are designed for a specific launch vehicle, therefore any new payloads should have little problem using the Delta IV Heavy as opposed to the Space Shuttle. The Delta Heavy has launched six times as of 2012. The first launch was a demonstration flight and was a partial failure. The payload for that launch was put into an incorrect orbit. The subsequent launches were all successful. Overall, the Delta IV Heavy is a good replacement to the Space Shuttle for U.S. and foreign unmanned payloads.

2. Atlas V Heavy Launch Vehicle (HLV)

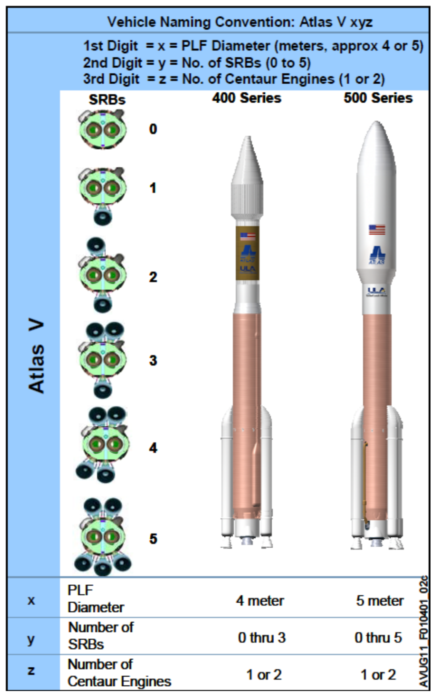

Figure 13. Atlas V Configurations (from United Launch Alliance, 2010)

The Atlas family of rockets is developed by Lockheed Martin. The current version of the Atlas V is launched for the U.S. government though Lockheed's and Boeing's joint venture, United Launch Alliance. Just like Boeing's Delta IV, Lockheed's Atlas V has a liquid core booster. It also has the capability to launch more mass into orbit by adding solid strap on motors to the side. While the Delta IV requires its solid rocket booster to be added in pairs, the Atlas V allows for an odd or even number of solid rocket boosters to be added. The Atlas V also allows for one more booster to be added then the Delta IV for a maximum of five boosters. These booster configurations are shown in Figure 13. The largest Atlas V currently produced and launched is the Atlas 551. It has five solid boosters strapped and a 5m payload fairing. (United Launch Alliance, 2010)

There is a proposed Atlas V Heavy option. This would be just like the Delta IV and have three of its core engines strapped together. On paper this launch vehicle is capable of putting more mass into orbit than the Delta IV Heavy, but no decision to actually build the Atlas V Heavy has been made. Therefore it is only proposed and would require significant investment. At this time it is unlikely the U.S. government would pursue the Atlas V Heavy as they have already invested in the Delta IV Heavy. The payload parameters are given for the Atlas 551 and proposed Atlas Heavy are given in Table 9. The values given are for a Low-Earth Orbit (LEO) of 400km at 28.5° inclination and a geosynchronous transfer orbit (GTO) of 35,786 x 185 km at 27° inclination. The Atlas V 551 is a good replacement to the Space Shuttle. Just like the Delta IV Heavy, there have only been a few of them launched. All of them have been successful, and Lockheed's track record in successful launches is excellent. Overall, the Atlas 551 is a suitable replacement to the Space Shuttle for U.S. and foreign unmanned payloads (United Launch Alliance, 2010; United Launch Alliance, 2010).

3. Ariane 5

The Ariane 5 is the European Space Agency's (ESA) heavy launch vehicle. It can service the International Space Station with the Automated Transfer Vehicle, on a Low Earth Circular orbit. The payload capabilities of the Ariane 5 are given in Table 9. The published launch capabilities for an altitude range between 200 and 400 km and 51.6° inclination. The performance varies between 19 and 21 metric tons, depending on the specific mission. While not stated, the lower value was listed for the higher altitude (400 km) and the higher value was listed for the lower LEO altitude (200 km). The Ariane 5 had some early failures in its history; it has since had numerous successes over the last decade. The Ariane 5 is a capable replacement to the Space Shuttle and is a proven launch vehicle. It is a foreign system that would require the U.S. to allow its payloads to be launched on foreign launch vehicles. Since the U.S. has strong relations with Europe and the ESA, it is unlikely that the U.S. would be denied access to its launch vehicle. However, the United States might be bumped if ESA had a payload they deemed a higher priority they a given U.S. payload (Arianespace, 2011).

4. Russian Proton

The Russian Proton is a launch vehicle with a long and proven track record going back to the 1960's. Few launch vehicles have had as much success or been operated for as long. The capabilities of the Russian Proton are given in Table 9. The given capabilities are for a LEO altitude of 180 km at an inclination of 51.5° and a GTO at an inclination of 31.1°. Just as with ESA's Ariane 5, the concern would not be with the Proton's capability, but it would be that the host nation for the launch system is foreign. The U.S. government would likely not use it as there would be concerns about U.S. payload priority and transportation to the launch range being utilized (International Launch Services, 2009).

5. Japanese H-IIB

The Japanese H-IIB has only been used to launch the H-II Transfer Vehicle (HTV) to deliver supplies to the ISS. It has been successful in delivering the HTV into orbit. The stated capabilities of the H-IIB are given in Table 9. The dimensions are for the payload faring, and limited data is provided on what orbital parameters are given for the payload capabilities given. The U.S. and Japan have a good relationship. The H-IIB launch vehicle could launch a payload similar to what the Space Shuttle could, the same concerns for Proton and Ariane 5 are for the H-IIB; as a foreign system it, there would be payload priority and transportation concerns (Nimura, Goto, Kondo, Egawa, Nakamura, & Arita, 2008; JAXA; JAXA, 2009).

B. FUTURE SYSTEMS

1. Falcon Heavy

SpaceX had this to say about their future Falcon Heavy in a press release. "Falcon Heavy is the most powerful rocket in the world and historically is second only to the Apollo-era Saturn V moon rocket. Capable of lifting 53 metric tons (117,000 pounds) to low Earth orbit and over 12 metric tons (26,000 pounds) to GTO, Falcon Heavy will provide more than twice the performance to low Earth orbit of any other launch vehicle. This will allow SpaceX to launch the largest satellites ever flown and will enable new missions. Building on the reliable flight proven architecture of the Falcon 9 launch vehicle, Falcon Heavy is also designed for exceptional reliability, meeting both NASA human rating standards as well as the stringent U.S. Air Force requirements for the Evolved Expendable Launch Vehicle (EELV) program, making it an attractive solution for commercial, civil and military customers" (Grantham, 2012).

According to SpaceX, the launch capability of the Falcon Heavy to LEO will be double that of the Delta IV Heavy, currently the biggest launch vehicle in the United States. To deliver this incredible launch capability, SpaceX is doing roughly the same thing as Boeing did with the Delta IV Heavy. SpaceX will take three of their Falcon 9 first stage modules and strap them to each other side by side. The stated capacities of the Falcon 9 and Falcon Heavy are given in Table 9. The mass to a 200 kg LEO and GTO are both given for an inclination of 28.5°. SpaceX currently has a posted GTO mass for their Falcon Heavy of 12,000 kg. This number will become more refined as SpaceX progresses closer to actually launching a Falcon Heavy, which they are anticipating as sometime in 2013 (SpaceX, 2012; SpaceX, 2012; SpaceX, 2012).

The Falcon Heavy would not only be a suitable replacement for the Space Shuttle, it may also be an improvement. With SpaceX's plan to have the Falcon Heavy human rated, this means they could potentially launch their Dragon capsule with seven astronauts, which they are working with NASA for under CCDev, on it. This means just like the Space Shuttle, the Falcon Heavy could theoretically launch seven astronauts and a massive payload into space on the same launch vehicle. However, the Falcon Heavy would likely be able to launch an even larger payload. The only drawback is unless they designed a new return vehicle or launched multiple dragon capsules; they would not be able to return much mass down to Earth along with the astronauts.

2. Chinese Long March 5

The Chinese Long March 5 is a liquid launch vehicle being developed by China Aerospace Science and Technology Corporation. They hope to launch the first Long March 5 in 2014. The Long March 5 will be a family of launch vehicles based around 2 engines and 3 modules. The largest of the Long March 5 configurations will be able to lift up to 25 metric tons to LEO (Low Earth Orbit) and 14 metric tons to a GTO (GEO transfer orbit). (CASC; CASC; Morring J. F., 2012; Perrett, *China Working On Big Range Of Space Engines*, 2012)

According to an Aviation Week article on China's future plans for their Long March Launch vehicles, "China is developing three basic rocket modules, with diameters of 2.25 meters, 3.35 meters and 5 meters and lengths that vary with their roles as first or second stages or side-mounted boosters. Matched with those modules are two new engines, the kerosene-fueled YF-100 in the two narrower bodies (hence module names, K2 and K3) and the liquid-hydrogen fueled, 50- ton-thrust YF-77 in the wider module (called H5)…. The Long March 5 core will be built up from one or two H5 modules, with various combinations of K3 and K2 boosters. The largest version, Long March 5E, is intended to deliver 14 tons to geostationary orbit, its low-orbit payload unstated." (Perrett, *Longer Marches*, 2010)

Figure 14. Proposed Long March 5 Launch Vehicle Family (from CASC)

The various proposed configurations of the Long March 5 family are shown in Figure 14. All of the versions will have the same 5-meter core. The three shorter versions will not have second stage and be used for LEO missions. The taller three versions will have a second stage and be used for GTO missions. Depending on the size of the payload, they will use three different combinations of strap-on boosters. The smallest will use four of the smaller 2.25 meters strap on boosters. The largest payload will use four of the larger 3.35 meters booster. Mid-sized payloads between those will use two of each of the strap-on boosters.

China's launch vehicle development is not quite up to the level of other space nations; however they are catching up quickly. Their launch vehicles do not have the proven track recorded of other systems, and they have not shown a capability to launch a in a sizable quantity over a period of time. When this is factored in along with the fact that U.S. and China political ties are strained at times, the Long March Vehicles is not a good fit to replace the Space Shuttle. If these obstacles are overcome, the Long March 5 could technically in the future replace the launch capability of the Space Shuttle, albeit foreign technology transfer concerns remain.

3. Russian Angara Rocket Family

The Angara family of launchers is Russia's next generation of launchers to be launched from Plesetsk, Russia. The family is under development at Khrunichev State Research and Production Space Center. The Angara family is based on a common core booster (CCB) that uses one RD -191 high-power oxygen/kerosene engine per CCB. The RD-191 is a new engine. It is derived from the four-chamber engine used earlier by the Energia launch vehicle and the RD 170/171 engine still in operation on the Zenith launch vehicle. Russia is hoping to reduce risk by using commonality in their design including common CCBs and building on their proven heritage and track record. (Khrunichev State Research and Production Space Center)

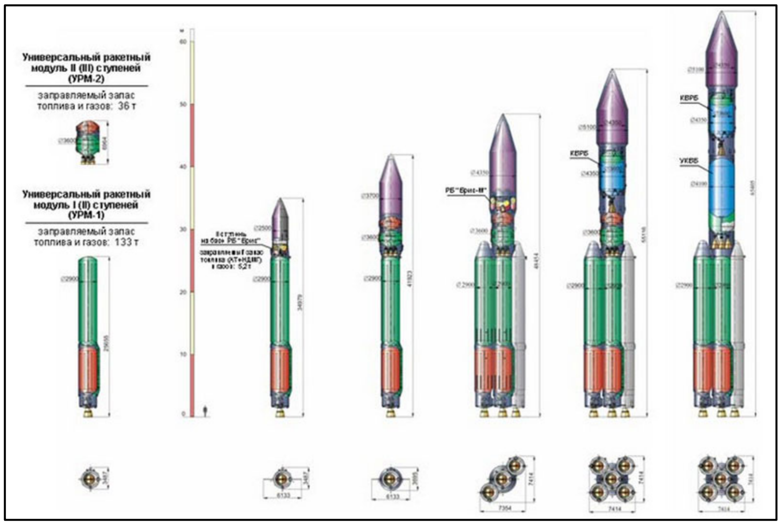

Figure 15. Angara Family (from Khrunichev State Research and Production Space Center)

Descriptions	Angara 1.2 (Small-lift)	Angara 3 (Medium-lift)	Angara A5 (Heavy-lift)	Angara A7 (Heavy-lift)
Lift-off mass, t	171	481	773	1133
Payload mass (kg)				
- LEO at 200 km, *i* = 63 °	3.8	14.6	24.5	35.0
- Geotransfer Orbit	-	3.6 (w/KVSK) 2.4 (w/Breeze M)	7.5 (w/KVTK) 5.4 (w/Breeze M)	12.5 (w/KVTK-A7)
- GSO (Geostationary)	-	2.0 (w/KVSK) 1.0 (w/Breeze M)	4.6 (w/KVTK) 3.0 (w/Breeze M)	7.6 (w/KVTK-A7)

Table 10. Angara Family Performance Data (after Khrunichev State Research and Production Space Center)

Unlike the U.S. Delta IV and Atlas V, the Angara family also does not incorporate any additional solid rockets. Angara instead uses multiple liquid cores strapped together just like the U.S. Delta IV Heavy. This highlights the different design approaches taken by the two companies and countries. The first number after the Angara name indicates how many CCBs will be used. The Angara 1, Angara 3, Angara 5, and Angara 7 will use one, three, five and seven CCBs, respectively. The payload capabilities for the Angara family are given in Table 9 and Table 10. If the U.S. was willing to utilize a Russian launch vehicle, the Angara 5 or 7 could be a good replacement for the Space Shuttle's payload launch capability. Russian launch vehicles have a very successful track record. With the current economic climate, there is concern that the program could be delayed or not receive funding (Khrunichev State Research and Production Space Center).

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V. REPLACEMENT OPTIONS FOR THE SPACE SHUTTLE'S SPECIALIZED MISSIONS

A. INTERNATIONAL SPACE STATION CARGO

There are many options available for delivering cargo to the International Space Station (ISS). Some of the options are new or future capabilities. While the Progress cargo vehicle has been around for decades, the rest are relatively new or not yet operational. A list of the previous (Space Shuttle), current, and future options to deliver cargo to the International Space Station (ISS) is given in Table 11.

Supply Vehicle		Up-Mass Total		Pressurized		Down-Mass
Name	Country	Mass (kg)	Volume (m^3)	Mass (kg)	Volume (m^3)	Mass (kg)
Space Shuttle	U.S.	18,300	83.6	Varies	Varies	Same
Current Launch Vehicles						
Cygnus	U.S.	2,000	18.9	2,000	18.9	None
ATV	Europe	6,600	*	3,200	48	None
HTV	Japan	6,000	30	5,200	14	None
Dragon	U.S.	6,000	24	*	10	3,000
Progress	Russia	2,230	*	1,800	7.6	None
Proposed Launch Vehicles						
Cygnus Enhanced	U.S.	2,700	27	2,700	27	None
Dragon Extended	U.S.	*	44	*	10	3,000
* Not Specified						

Table 11. ISS Resupply Systems Capabilities. (after ERAMUS Centre, ESA, 2005; NASA, 2010; European Space Agency, 2010; European Space Agency, 2011; Isakowitz, Hopkins, & Hopkins, 2004;) (JAXA; Japan Aerospace Exploration Agency, 2012; Orbital Sciences Corporation, 2012; SpaceX, 2012; SpaceX)

1. Automated Transfer Vehicle (ATV)

The Automated Transfer Vehicle (ATV) is a cargo vehicle developed by the European Space Agency. ATV is designed for resupplying the International Space Station (ISS) and is launched on ESA's Ariane 5 launch vehicle. A size comparison of ATV to Apollo and Progress is shown in Figure 16. ATV measures 10.7m in length, 4.5m in diameter, and has a solar array span of 22.3m when deployed. There are two main modules to ATV, the Integrated Cargo Carrier and the ATV Service Module. The ATV Service Module is essentially the bus of the spacecraft. It holds the power, computer, avionics, and communication systems required to power and pilot ATV to ISS. The Integrated Cargo Carrier does just as its name implies, it holds the cargo to be delivered to the ISS. This cargo can be in the unpressurized section or the $48m^3$ pressurized cargo section (European Space Agency, 2010; European Space Agency, 2011).

ATV can carry up to 6,600 kg of cargo to the ISS. This cargo configuration is a customized ratio of dry and wet cargo. The wet cargo consists of propellant, water, and gases. Up to 4,000 kg of propulsive support propellant can be loaded. This is the monomethylhydrazine (MMH) and mixed oxides of nitrogen (MON3) that are used by ATV to boost or change the ISS orbit. The ATV is the largest thrust capability of the transport vehicles that currently can visit the ISS. These boost or orbit changes are necessary to keep the ISS in its desired orbit and fight the effects of atmospheric drag. Up to 860kg of a second type of refueling propellant can also be loaded on ATV. This second propellant is used by the ISS thrusters for station keeping when ATV is not attached. More specifically, this propellant is unsymmetrical dimethylhydrazine (UDMH) and nitrogen tetroxide (N2O4), which is used by the ISS. Besides the two types of propellants, up to 855 kg of water and 102 kg of gases (nitrogen, oxygen, or air) can be delivered with ATV to ISS. This water and gas is used to support the astronauts and life on the ISS. The dry cargo that ATV can carry is located in the Integrated Cargo Carrier. This dry cargo is up to 3,200 kg of food, clothing, spare parts, or anything else that may be needed on ISS. Not every category of dry and wet cargo can be maxed out. A balance has to be made to stay under the 6,600 kg max payload limit. For example, ATV-3 “Edoardo Amaldi” carried 6,595 kg of total cargo. 2,200 kg of that cargo was dry cargo, and 4,395 kg of it was wet cargo. The wet cargo was broken down into: 3,150 kg of ISS propulsive support, 860 kg of refueling propellant, 285 kg of water, and 100 kg of gas (oxygen and air) (European Space Agency, 2010; European Space Agency, 2012).

The capabilities of the ATV to resupply the ISS are also given in Table 11. The ATV is one of the largest vehicles out there. There have been three successful ATV launches to date. One more launch is scheduled each year until at least 2014. While it cannot deliver the same mass or volume of items to the ISS that the Space Shuttle did, it can and does satisfactory fulfill the ISS resupply mission. The ATV burns up in the Earth's atmosphere after it separates from the ISS, enabling it to take some waste away from the ISS. However, it cannot take any down mass or items back to Earth from the ISS.

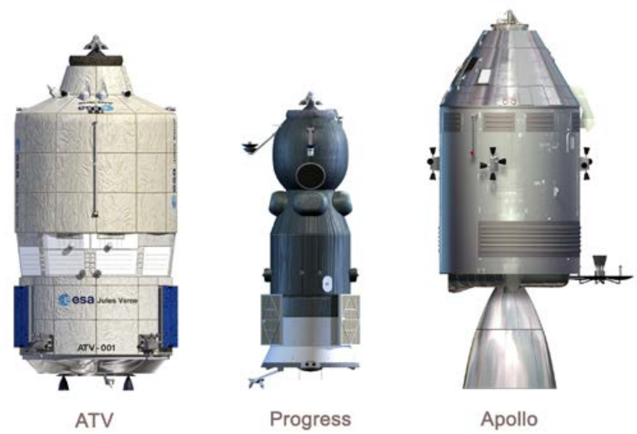

Figure 16. ATV compared to Progress & Apollo (from European Space Agency, 2003)

2. H-II Transfer Vehicle (HTV)

H-II Transfer Vehicle (HTV) was developed by Japan Aerospace Exploration Agency and is launched on top of their H-IIB launch vehicle. HTV is nicknamed "KOUNOTORI," which means "white stork." The sections and rough size of HTV is shown in Figure 17. HTV is 9.8m long and has a diameter of 4.4m. HTV can carry a payload of up to 6,000kg. The maximum pressurized payload allowed can be up to 5,200kg and the max unpressurized can be up to 1,500 kg. All together HTV has a max launch mass of 16,500kg. HTV has no deployable solar arrays for power. Its solar arrays are body mounted to the outside of the spacecraft. Just like other resupply spacecraft, HTV can carry a varying combination of food, water, supplies, and spares to the ISS. It can also carry waste from the ISS that burns up on re-entry into Earth's atmosphere

(JAXA; Japan Aerospace Exploration Agency, 2012; Japan Aerospace Exploration Agency, 2012).

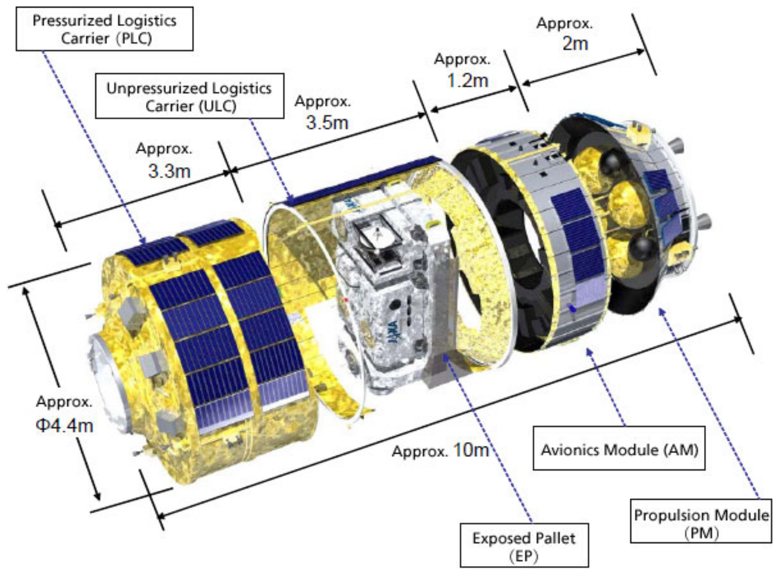

Figure 17. HTV Components (from Japan Aerospace Exploration Agency, 2012)

There have been four successful launches of the HTV spacecraft to resupply the ISS to date. There are at least two more HTV missions planned at one launch per year. It does not have a down mass capability, but HTV is a capable replacement to the Space Shuttle for the ISS resupply mission.

3. Dragon Cargo Spacecraft

The Dragon Cargo spacecraft is Space Exploration Technologies' (SpaceX) vehicle designed for NASA Commercial Orbital Transportation Services (COTS) contract. The Dragon spacecraft is the only commercial spacecraft to launch a payload and dock with the ISS. Previously only four governments (U.S., Russia, Japan and ESA) had successfully been able to reach ISS. Unlike all other current ISS resupply spacecraft, Dragon is also capable of returning 3,000 kg of cargo to Earth in its $10m^3$-pressurized capsule. The Dragon capsule has an area below it's pressurized capsule it calls the "trunk." The trunk provides $14m^3$ of unpressurized cargo space. The trunk is also where its solar arrays attach and deploy from. Including the pressurized Dragon capsule and trunk space, the Dragon spacecraft can take 6,000 kg of payload to the ISS. The Dragon capabilities are also given in Table 11. (SpaceX, 2012; SpaceX)

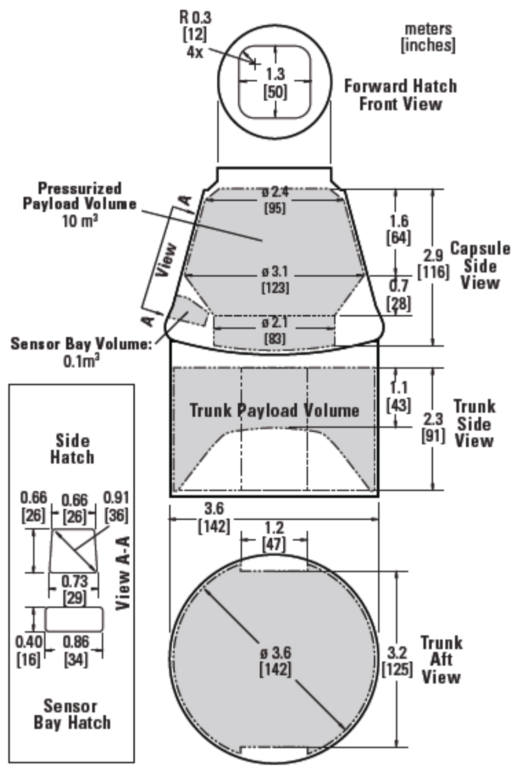

Figure 18. Dragon Configuration (from SpaceX)

A diagram of the Dragon spacecraft layout and dimensions is given in Figure 18. The Dragon spacecraft is not as large as the Space Shuttle and therefore does not have the payload capability of the Space Shuttle. The capability of Dragon spacecraft is however in similar with the rest of the current ISS resupply spacecraft. The Dragon spacecraft is the only current resupply spacecraft that can return a payload from the ISS back to Earth. Due to its payload delivery and return to Earth capability the Dragon spacecraft is very capable to replace the Space Shuttle in the ISS resupply mission. The ability of the Dragon spacecraft to return items from the ISS to Earth is a Space Shuttle capability that no other current ISS resupply spacecraft possesses. It is also the only current U.S.

domestic option. NASA has awarded multiple launches per year to SpaceX for the Dragon to ISS cargo mission. If the other COTS option does not materialize as planned, then the number of launches for SpaceX's Dragon will only grow.

4. Cygnus Spacecraft

Orbital Sciences Corporation is developing the Cygnus spacecraft under the Commercial Orbital Transportation Services (COTS) Space Act Agreement with NASA. Orbital has decided to launch from NASA's Virginia based Wallops Flight Facility using the Antares (formally Taurus II) medium-class launch vehicle. Orbital launched an Antares demonstration mission on 21 April 2013. Orbital is on contract to use Cygnus for eight ISS resupply flights under the NASA Commercial Resupply Service (CRS) contract between 2013 and 2016. The first of which is planned for later in 2013. During these CRS missions, Cygnus will carry crew supplies, spare parts, and scientific experiments to the ISS. An artist rendering of Cygnus is shown in Figure 19 (Orbital Sciences Corporation, 2012; Orbital Sciences Corporation, 2013).

Figure 19. Artist rendering of Cygnus spacecraft (from Orbital Sciences Corporation)

There are only two main parts to Cygnus, the common service module and the pressurized cargo module. In common satellite terms, the common service module is the bus and the cargo module is the payload. To keep the risk down for the Cygnus system, Orbital is drawing from their private and their partners' existing and flight-proven technologies. The "bus" or service module uses parts from Orbital's flight-proven LEOStar and GEOStar satellite lines. The "payload" or pressurized cargo module is based on the Multi-Purpose Logistics Module (MPLM), which was developed for NASA by Thales Alenia Space. Cygnus is also able to carry waste from the ISS for disposal. This waste will burn up on reentry and will not make it back to Earth. Orbital plans for it's first three CRV missions are to be of the original design. The next five CRV missions will use an enhanced version that will be slightly larger and able to carry more mass. The capabilities of both the original and enhanced versions are given in Table 11 (Orbital Sciences Corporation, 2012).

While Cygnus does not have nearly the payload capability of the Space Shuttle, it will certainly be able to support the ISS resupply mission. Cygnus does not have the ability to carry any payload back to Earth. There are advantages for Cygnus. It utilizes a launch system and range that are not heavily utilized. This in theory means they could be more responsive and have more availability and flexibility in launch times.

5. Progress Spacecraft

The Progress cargo vehicle was developed by the Russian Federal Space Agency. It has been used for decades, since Russia used it to provide supplies to their Mir and their other space station. The Progress cargo spacecraft currently used to service the ISS is the latest upgraded versions of the Progress vehicle. Progress cargo vehicle is based on the Soyuz Spacecraft and is launched on top of a version of the Soyuz rocket. It has a launch mass of 7,150 kg and measures 7.23m in length, 2.72m in diameter max, and a solar array span of 10.60m. A figure of progress compared to ATV is shown in Figure 16. The Progress vehicle is made up of three main parts, the Cargo Module, the Refueling Module, and Instrumentation/Propulsion Module (ERAMUS Centre, ESA, 2005; NASA, 2010).

Between the Cargo and Propellant Modules, Progress can carry a maximum cargo mass of 2,230 kg as shown in Table 11. The Cargo Compartment has a volume of 7.6m^3

and maximum dry cargo mass of 1,800 kg. After the cargo is removed and before the Progress undocks, the crew refills it with trash, unneeded equipment and wastewater, which will burn up with the spacecraft when it re-enters the Earth's atmosphere. The Cargo Module can hold 1,000 to 1,700 kilograms (2,205 to 3,748 pounds) of trash. The Propellant Module can hold a maximum of 1,950 kg. The Progress M1 Refueling Module has eight propellant tanks (four contain fuel and four contain oxidizer). The Progress M has four tank propellant tanks (two for fuel and two for oxidizer) and two water tanks. The M1 has no water tanks. The last module, the "Instrumentation/Propulsion Module contains the electronic equipment, or avionics, for the Progress' systems and sensors. It is similar in design to the Soyuz Instrumentation/Propulsion Module. Any fuel in this module that is not used to get the Progress to the Station or for undocking and deorbit can be used to boost the altitude of the Space Station. Surplus fuel amounts can vary from 185 to 250 kilograms" (ERAMUS Centre, ESA, 2005; NASA, 2010).

The Russians have used the Progress cargo vehicle since the late 1970's. It has been a workhorse for delivering supplies to their space stations and now the ISS. Russia has been using the Progress cargo vehicle to deliver supplies to the ISS since the very beginning. There is little to suggest that Russia would stop supporting supply deliveries to the ISS. While it takes many more Progress launches to deliver the same amount of supplies as the Space Shuttle, Progress is a suitable replacement of the ISS supply mission left after the Space Shuttle retired.

B. DOWN-MASS CARGO

There are few options to bring cargo back to Earth from space. The Soyuz capsule can take a very limited amount of cargo back with its human cargo. This is however a very small amount and therefore not discussed further in this section. Of all the supply vehicles that currently service the ISS, only SpaceX's Dragon Spacecraft can return cargo back to Earth. The United States Air Force (USAF) has a space plane known as the X-37B that can take items into space and then return them to Earth.

1. Dragon Spacecraft

Unlike all the other current ISS resupply spacecraft, SpaceX's Dragon spacecraft is the only one capable of returning cargo safely back to Earth. It is capable of returning 3,000 kg of cargo in its 10m^3-pressurized capsule. Beyond using the Dragon spacecraft to carry cargo to the ISS, SpaceX also plans to accommodate stand-alone missions to LEO (Low Earth Orbit). For these missions SpaceX is calling its Dragon cargo spacecraft, DragonLab. This is due to the fact that the Dragon spacecraft would be essentially a lab in space. In its current configuration, the DragonLab would not be able to retrieve items from space and return them to Earth, therefore it would only be able to return what it carried into orbit. It is however possible for a manned mission to meet up with the DragonLab and work on experiments away from ISS (SpaceX, 2012).

The Dragon spacecraft does a good job replacing the Space Shuttle for Down-Mass capability from the ISS albeit for smaller cargo loads. The DragonLab would also do a good job for science experiments in LEO away from ISS. The main limitation of the Dragon spacecraft compared to the Space Shuttle is the size of the payload it can carry to and from orbit. The Dragon spacecraft would also have a problem deploying and retrieving a payload away from the ISS. Despite this, the Dragon spacecraft is the best and only unclassified replacement to the Space Shuttle for a Down-Mass capability especially from the ISS.

2. USAF X-37B Space Plane

The USAF X-37B has a long and complicated history. According to the Boeing Backgrounder sheet, "The X-37B orbital test vehicle program began in 1999, when Boeing and the National Aeronautics and Space Administration (NASA) began researching the vehicle concepts. Later, DARPA divided the program into two vehicles, an X-37 approach and landing test vehicle (ALTV) and an X-37 orbital vehicle. The X-37 ALTV was designed to validate flight dynamics and extend the flight envelope beyond the low speed/low altitude tests conducted by NASA from 1998 through 2001 on the X-40A, a sub-scale version of the X-37 developed by Air Force Research Labs.

DARPA completed the X-37 ALTV program in September 2006 by successfully executing a series of captive carry and free flight tests from the Scaled Composites White Knight aircraft. The X-37 orbital vehicle envisioned by NASA was never built, but its design formed the basis for the Air Force's X-37B Orbital Test Vehicle program" (Boeing, 2012).

The X-37B program transitioned to the U.S. Air Force in 2004 under the Rapid Capabilities Office. The X-37B is similar to the Space Shuttle. It is roughly one quarter the size of the Space Shuttle. Its lifting body design is related in heritage to the Space Shuttle and it has a similar landing profile to the Space Shuttle. While the X-37B is a predominately classified program, a few things have been published by Boeing and the US Air Force about it. The X-37B on orbit is 29' 3" in length, 9'6" in height, and has a wing space of 14' 11". The launch weight of the X-37B is stated as 11,000 pounds for a 110 to 500 mile orbit. The X-37B is launched on top of an Atlas V in the 501 configuration. The means it requires no strap-on rocket boosts and has a 5m fairing (Boeing, 2012; U.S. Air Force, 2010).

Figure 20. X-37B with half of its Atlas V five-meter fairing (from U.S. Air Force, 2011)

The X-37B is launched and was designed to operated and/or test items in its 7ft by 4ft experiment bay. Just like the Space Shuttle did on a number of missions, The X-37B can test items in space over a period of time to see how they respond or degrade. Lt. Col. Tom McIntyre, X-37B program manager, addressed this capability in a recent press release. "With the retirement of the Space Shuttle fleet, the X-37B OTV program brings a singular capability to space technology development, the return capability allows the Air Force to test new technologies without the same risk commitment faced by other programs" (30th Space Wing Public Affairs, 2012; Boeing, 2012).

There are only two of the X-37B space planes. Each has flown at least one mission to date, however there are plans for each X-37B to be launched again in the future. They are designed to be reusable just like the Space Shuttle. The Air Force's first X-37B was launched on 22 April 2010 from Cape Canaveral Air Force Station. After slightly over 224.34 days in space, it performed a successful autonomous landing at Vandenberg AFB on 03 December 2010. While the X-37B was designed for an on orbit mission of 270 days, the second X-37B mission lasted much longer. The second X-37B space plane was launched on 05 March 2011. After roughly 469 days in space, it returned on 16 June 2012. The first X-37B launched again later in Oct 2012 (30th Space Wing Public Affairs, 2012; U.S. Air Force, 2011).

The X-37B can take items into space and test or use them, and then return them back to Earth. Due to the classified nature of the program, it is not likely that a manned mission such as the ISS or SpaceX Dragon space vehicle will rendezvous with it. This limits its scientific missions. Unlike the Space Shuttle, the X-37B has a small payload capability. That would limit the amount of tests/experiments that could be done. It also means the X-37B could not retrieve any object or satellite of decent size and return them to Earth. In spite of those limitations, many things can be done remotely or be programmed to run automatically. While the X-37B can fulfill the Space Shuttle Down-Mass capability for smaller payloads, the X-37B only does remote controlled/automated classified missions for the U.S. Therefore, the X-37B is not a suitable substituted for the Space Shuttle down-mass capability.

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VI. CONCLUSION

A. SUMMARY OF FINDINGS

There have been several breaks in the United States' human space flight capability, the longest being the timeframe between the last Apollo mission on 24 July 1975 and the first Space Shuttle mission on 12 April 1981. This break was needed to fund the Space Shuttle program in an era of reduced NASA budgets. The United States and NASA are currently in a similar situation. Reduced budgets forced NASA to retire the Space Shuttle in order to focus and reserve funding for future programs. The difference between now and the gap after Apollo is that the United States has many more space launch and space vehicle payload options from U.S. companies and foreign nations.

The replacement options for the Space Shuttle's human space flight, payload, ISS resupply, and down-mass capabilities were discussed in this thesis. No one system can fully replace the Space Shuttle. Many systems from multiple nations can place as large of a payload in size and mass into orbit. Also, many nations have systems that can take supplies to the ISS. Future U.S. systems will be able to carry the same amount of people (seven) as the average Space Shuttle mission. However, it is not possible with current or planned systems for down-mass capability for an item as large in size and/or mass as what the Space Shuttle was capable of accommodating. This limitation makes it impossible with current or planned systems to fully replace the Space Shuttle's capabilities.

There are many options available to the United States and International nations/organizations for payload launch and ISS resupply capabilities. The United States government historically has only used domestic launch vehicles. This policy limits the options available to the United States government and it's agencies. However, if all the currently planned programs come to fruition, the U.S. will have multiple options for both payload launch and ISS resupply. For heavy payload launch, the U.S. has the following domestic options: the Boeing Delta IV, the Lockheed Martin Atlas V, and if future testing is successful the SpaceX Falcon 9 Heavy. For ISS resupply, the U.S. has the SpaceX Dragon spacecraft and, if successful, the Orbital Sciences' Cygnus spacecraft.

There are few options available for human space flight and down-mass capability to the U.S. government and other nations/organizations. Currently, the options for manned space flight are the Russian Soyuz and Chinese Shenzhou. There have been few Shenzhou launches to date and, so far, China has not had anyone outside their nation participate in their Shenzhou program. This only leaves the Russian Soyuz. The United States may have up to three more options once the Commercial Crew Integrated Capability (CCiCap) program vehicles take flight. The SpaceX Dragon, the Boeing CST-100 and the Sierra Nevada Dreamchaser spacecraft will be available for use if testing and development is successful in the next few years and the necessary government funding is provided. The down-mass capability is very limited. Currently, only the Dragon spacecraft has an unclassified dedicated down-mass capability. Other programs such as the Dreamchaser or CST-100 may provide a down-mass capability if they are successful and take flight.

B. LIMITATIONS AND FUTURE WORK

This thesis had two main limitations. The first was the availability of open source information. This thesis was limited to information published in unclassified publications, websites, company literature, or other open source resources. Several companies/nations presented extensive open source information about their system(s), while others had very little information available. This information access and availability somewhat limited the ability to completely or accurately evaluate some programs for their suitability to fulfill a Space Shuttle capability.

The second main limitation of this thesis is the inability to predict the future outcome of a given program or system. Some of the programs in this thesis may not come to fruition, while other options not addressed in the thesis may develop or become a successful reality. Therefore, this thesis also did spend much time addressing hypothetical or theoretical options that could possibly come to fruition in the future. As a result of these two limitations, a few basic questions will have to be addressed in a future review:

Will the envisioned capabilities of the space systems discussed in this thesis change?

The capabilities of any of the programs mentioned in this thesis could very well develop differently than that currently published or advertised in the open references. This could be attributed to changes during development, the unwillingness to divulging the systems' true capabilities, or modifications done to improve the systems.

Will the systems discussed in the thesis be fielded?

With economic times being tough and limited space contracts available, it is likely that not all of the systems mentioned in this thesis will become a reality or actually launch. For example, it is unlikely that the Dragon, CST-100, and Dream Chaser will all make it into space. NASA will likely only fund one or possibly two long term. Therefore, of the three systems it is likely that only one or two of them may actually launch into space. It is also likely that only one would be carrying out routine space missions to space in 5 to 10 years with the others being cancelled due to lack of funding or technical issues.

Will additional programs or systems be developed, providing additional options?

New companies and technologies are being developed each year. It certainly is possible that a new company will emerge similar to SpaceX, which will provide a space launch capability. Other companies, such as Virgin Galactic, may start launching tourists into space. The realization of these systems could then open up a proven new market and potentially draw in additional space competitors. New technology could then be developed that would provide additional options not currently identified.

Has the need, political climate, or mission in space changed?

The need to launch items into space may change. Spacecraft may become smaller and routinely require smaller mass/volume launch capability. The opposite could happen as well and even larger spacecraft become needed than those currently available or envisioned. Also, other nations could merge their space programs together and foster more joint and combined space ventures. These joint efforts could either increase the number of systems needed or reduce the need for desired systems

C. CONCLUSION

The loss of the Space Shuttle program left the space community without a capable system that provided truly unique capabilities. However, the space launch industry is currently undergoing significant and rapid change. Many new programs are under development and making promising progress. When multiple systems are utilized, most of the capability the Space Shuttle provided can be reproduced today. The noticeable exceptions being a much reduced down-mass capability and the loss of the ability to launch an astronaut crew along with a large payload into space. While the loss of the Space Shuttle was a significant impact to the U.S. launch capability, there are fortunately many current and future systems that may eventually fulfill the specific mission capabilities the Space Shuttle once provided.

LIST OF REFERENCES

30th Space Wing Public Affairs. (2012, June 16). *X-37B Orbital Test Vehicle lands at Vandenberg.* Retrieved September 16, 2012, from Vandenberg Air Force Base: http://www.vandenberg.af.mil/news/story.asp?id=123306242

Amos, J. (2012, June 29). *China's Shenzhou-9 spacecraft returns to Earth.* Retrieved July 20, 2012, from BBC News: http://www.bbc.co.uk/news/world-asia-china-18636819

Arianespace. (2011, July). *Ariane 5 User's Manual.* Retrieved May 07, 2012, from Arianespace: http://www.arianespace.com/launch-services-ariane5/Ariane5_users_manual_Issue5_July2011.pdf

BBC News. (2009, April 07). *Soyuz successor contract awarded.* Retrieved April 15, 2012, from BBC News: http://news.bbc.co.uk/2/hi/science/nature/7987399.stm

Bilstein, R. E. (2004, August 6). *Stages to Saturn.* Retrieved November 28, 2010, from NASA History Office: http://history.nasa.gov/SP-4206/sp4206.htm

Boeing. (2012, April). *Backgrounder: X-37B Orbital Test Vehicle.* Retrieved September 16, 2012, from Boeing Company: http://www.boeing.com/defense-space/ic/sis/x37b_otv/bkgd_x37_0311.pdf

Borenstein, S. (2011, July 05). *Shuttle cost: More than AIG bailout, less than war.* Retrieved September 23, 2012, from NBC News: http://www.msnbc.msn.com/id/43631772/ns/technology_and_science-space/t/shuttle-cost-more-aig-bailout-less-war/#.UF-3aEK-3dk

Burghardt, M. (2011, August). *CCDev2 CST-100 Overview.* Retrieved March 25, 2012, from The Boeing Company: http://www.boeing.com/defense-space/space/ccts/docs/CCDev2%20Boeing%20CST-100%20Overview.pdf

CASC. (n.d.). *Long March-5 (LM-5).* Retrieved May 07, 2012, from China Aerospace Science and Technology Corporation (CASC): http://www.spacechina.com/n16421/n17215/n17269/n19031/c125250/content.html

CASC. (n.d.). *New Launch Vehicle Family.* Retrieved May 07, 2012, from China Aerospace Science and Technology Corporation (CASC): http://www.spacechina.com/n16421/n17215/n17269/n19031/c125240/content.html

Cassidy, J. L., Johnson, R. I., Leveye, J. C., & Miller, F. E. (1964, December). *NASA.* Retrieved November 06, 2010, from The Mercury- Redstone Project: http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19670028606_1967028606.pdf

Cortright, E. M. (Ed.). (1975). *Apollo Expeditions to the Moon.* Retrieved November 28, 2010, from NASA History Office: http://history.nasa.gov/SP-350/cover.html

Dun, A. J., & Waring, S. P. (1999). *Chapter VIII: The Space Shuttle: Development.* Retrieved July 24, 2011, from Power to Explore: A History of Marshall Space Flight Center, 1960-1990: http://history.msfc.nasa.gov/book/chpteight.pdf

ERAMUS Centre, ESA. (2005, September 09). *Progress Factsheet.* Retrieved September 09, 2012, from ESA Portal: http://wsn.spaceflight.esa.int/docs/Factsheets/34%20Progress%20LR.pdf

European Space Agency. (2011, June 16). *ATV cargo capacity*. Retrieved July 29, 2012, from ESA Portal: http://www.esa.int/SPECIALS/ATV/SEM2Z432VBF_0.html

European Space Agency. (2010, March 9). *ATV configuration.* Retrieved July 29, 2012, from ESA Portal: http://www.esa.int/SPECIALS/ATV/SEM4RYOR4CF_0.html

European Space Agency. (2012). *ATV Edoardo Amaldi info kit English.* Retrieved July 29, 2012, from ESA Portal: http://download.esa.int/docs/ATV/Information_kit_ATV-3_FINAL.pdf

European Space Agency. (2003, December 10). *compare atv.* Retrieved July 29, 2012, from ESA Portal: http://esamultimedia.esa.int/images/atv/compareatv_low.jpg

European Space Agency. (n.d.). *Soyuz TMA.* Retrieved July 31, 2011, from ESA: http://esamultimedia.esa.int/docs/hsf_research/ISS_User_Guide/35_Soyuz_web.pdf

Gerstenmaier, W. (2012, July 31). *Selection Statement for Commercial Crew Integrated Capabilities.* Retrieved September 22, 2012, from NASA: http://commercialcrew.nasa.gov/document_file_get.cfm?docID=645

Grantham, K. (2012, May 29). *Intelsat Signs First Commercial Falcon Heavy Launch Agreement with SpaceX.* Retrieved June 17, 2012, from SpaceX: http://www.spacex.com/press.php?page=20120529

Grinter, K. (Ed.). (2008, March 27). *Apollo: The Moon Missions*. Retrieved October 03, 2010, from NASA Human Space Flight: http://www-pao.ksc.nasa.gov/kscpao/history/apollo/flight-summary.htm

Grinter, K. (Ed.). (2000, September 11). *Gemini Missions*. Retrieved March 19, 2011, from NASA Human Space Flight: http://www-pao.ksc.nasa.gov/kscpao/history/gemini/gemini-manned.htm

Grinter, K. (Ed.). (2000, September 26). *Goals of the Gemini Program*. Retrieved March 19, 2011, from NASA Human Space Flight: http://www-pao.ksc.nasa.gov/kscpao/history/gemini/gemini-goals.htm

Grinter, K. (Ed.). (2000, September 09). *Skylab Flight Summary*. Retrieved October 03, 2010, from NASA Human Space Flight: http://www-pao.ksc.nasa.gov/kscpao/history/skylab/flight-summary.htm

Grinter, K. (Ed.). (2002, April 05). *The Flight of Apollo Soyuz*. Retrieved October 03, 2010, from NASA Human Space Flight: http://www-pao.ksc.nasa.gov/kscpao/history/astp/flight-summary.htm

Grinter, K. (Ed.). (2000, September 27). *The Gemini Flight Summary*. Retrieved October 04, 2010, from NASA Human Space Flight: http://www-pao.ksc.nasa.gov/kscpao/history/gemini/flight-summary.htm

Grinter, K. (Ed.). (2000, September 29). *The Mercury Project - Flight Summary*. Retrieved October 04, 2010, from NASA Human Space Flight: http://www-pao.ksc.nasa.gov/kscpao/history/mercury/flight-summary.htm

Grinter, K. (Ed.). (2000, September 27). *The Mercury Project - Goals*. Retrieved March 19, 2011, from NASA Human Space Flight: http://www-pao.ksc.nasa.gov/kscpao/history/mercury/mercury-goals.htm

Grinter, K. (Ed.). (2000, September 29). *The Mercury Project - Unmanned Missions*. Retrieved March 19, 2011, from NASA Human Space Flight: http://www-pao.ksc.nasa.gov/kscpao/history/mercury/mercury-unmanned.htm

International Launch Services. (2009, October). *Proton Mission Planner's Guide Revision 7.* Retrieved May 08, 2012, from Proton Rocket Commercial Launch Sales & Mission Managment: http://www.ilslaunch.com/sites/default/files/pdf/Proton%20Mission%20Planner%27s%20Guide%20Revision%207%20%28LKEB-9812-1990%29.pdf

Isakowitz, S. J., Hopkins, J. B., & Hopkins, J. J. (2004). *International Reference Guide to Space Launch Systems* (4th ed.). Reston, VA: AIAA.

Japan Aerospace Exploration Agency. (2012). *Major Characteristics.* Retrieved August 24, 2012, from JAXA: http://www.jaxa.jp/projects/rockets/htv/design_e.html

Japan Aerospace Exploration Agency. (2012). *Overview of the KOUNOTORI (HTV).* Retrieved August 24, 2012, from JAXA: http://www.jaxa.jp/countdown/h2bf2/overview/htv_e.html

JAXA. (n.d.). *H-IIB Pamphlet.* Retrieved April 29, 2012, from Japan Aerospace Exploration Agency (JAXA): http://www.jaxa.jp/pr/brochure/pdf/01/rocket05.pdf

JAXA. (n.d.). *HTV: H-II Transfer Vehicle "KOUNOTORI".* Retrieved August 24, 2012, from JAXA: http://www.jaxa.jp/pr/brochure/pdf/01/rocket03.pdf

JAXA. (2009, September 09). *HTV-1 Mission Press Kit.* Retrieved May 08, 2012, from Japan Aerospace Exploration Agency (JAXA): http://www.jaxa.jp/countdown/h2bf1/pdf/presskit_htv_e.pdf

Kaplan, J. A. (2011, July 27). *Russia Plans to Sink the International Space Station in 2020.* Retrieved September 29, 2012, from Fox News: http://www.foxnews.com/scitech/2011/07/27/russia-plans-to-sink-international-space-station-in-2020/

Kauderer, A. (Ed.). (2011, June 7). *Shuttle Missions*. Retrieved July 24, 2011, from NASA: http://www.nasa.gov/mission_pages/shuttle/shuttlemissions/list_main.html

Khrunichev State Research and Production Space Center. (n.d.). *Angara Launch Vehicles Family.* Retrieved May 07, 2012, from Khrunichev State Research and Production Space Center: http://www.khrunichev.ru/main.php?id=44

Khrunichev State Research and Production Space Center. (n.d.). *The Angara family of launch vehicles.* Retrieved July 21, 2012, from Khrunichev State Research and Production Space Center: http://www.khrunichev.ru/img/al/1223521010.jpg

Marshall Space Flight Center History Office. (n.d.). *Biography of Wernher Von Braun.* Retrieved September 30, 2012, from NASA: http://history.msfc.nasa.gov/vonbraun/bio.html

McAlister, P. R. (2011, April 04). *Selection Statement for Commercial Crew Development Round 2.* Retrieved January 16, 2012, from Kennedy Space Center Procurement Office: http://procurement.ksc.nasa.gov/documents/SelectionStatement-Final_Signed.pdf

Morring, F. J. (2011, April 25). *Five Vehicles Vie To Succeed Space Shuttle.* Retrieved October 01, 2011, from Avitaiton Week: http://www.aviationweek.com/aw/generic/story_generic.jsp?channel=awst&id=news/awst/2011/04/25/AW_04_25_2011_p24-313867.xml&headline=Five%20Vehicles%20Vie%20To%20Succeed%20Space%20Shuttle

Morring, J. F. (2012, April 16). *Concepts Abound As Launch Marketplace Loosens.* Retrieved May 07, 2012, from *Aviation Week* & Space Technology: http://www.aviationweek.com/Article.aspx?id=/article-xml/AW_04_16_2012_p49-444899.xml#

NASA. (2004, April 03). *A Quick Overview and Timeline of Shuttle-Mir*. Retrieved October 03, 2012, from NASA: http://spaceflight.nasa.gov/history/shuttle-mir/references/r-timeline.htm

NASA. (2000, August 31). *External Tank.* Retrieved October 07, 2012, from NASA: http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/et.html

NASA. (2012, July 25). *Facts and Figures.* Retrieved September 23, 2012, from NASA: http://www.nasa.gov/mission_pages/station/main/onthestation/facts_and_figures.html

NASA. (2012, May 14). *Gemini 12.* Retrieved September 30, 2012, from NASA: http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1966-104A

NASA History Division. (2005, July 1). *ASTP - Chronology*. Retrieved December 31, 2010, from NASA History Division: http://history.nasa.gov/astp/chronology.html

NASA. (2010). *Main Soyuz Parts.* Retrieved July 31, 2011, from NASA: http://www.nasa.gov/images/content/112684main_soyuzparts_lg.jpg

NASA. (1988). *Mission Preparation and Prelaunch-Operations*. Retrieved October 14, 2010, from NSTS Shuttle Reference Manual: http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/stsover-prep.html

NASA. (2005). *NASA Range Saftey Program 2005 Annual Report*. Retrieved September 11, 2001, from NASA: http://kscsma.ksc.nasa.gov/Range_Safety/Annual_Report/2005/PrintPages/China.pdf

NASA Newsroom. (2011, May 24). *Press Release: 11-164. NASA Announces Key Decision For Next Deep Space Transportation System.* Retrieved July 30, 2011, from NASA: http://www.nasa.gov/home/hqnews/2011/may/HQ_11-164_MPCV_Decision.html

NASA Newsroom. (2011, July 01). *Press Release: 11-218. NASA Administrator Discusses Agency's Future Endeavors.* Retrieved July 31, 2011, from NASA: http://www.nasa.gov/home/hqnews/2011/jul/HQ_11-218_Bolden_Speech.html

NASA Newsroom. (2011, July 18). *Press Release: 11-232. NASA Begins Commercial Partnership With United Launch Alliance.* Retrieved July 30, 2011, from NASA: http://www.nasa.gov/home/hqnews/2011/jul/11-232_ULA_Agreement.html

NASA Public Affairs. (2009, October 22). *NASA Press Breifing "U.S. Human Space Flight Review Committee Report".* Retrieved March 08, 2010, from NASA: http://www.nasa.gov/pdf/396987main_102208-PressConferenceTranscript.pdf

NASA. (2010, October 23). *Russian Progress Spacecraft.* (J. I. Petty, Ed.) Retrieved September 09, 2012, from NASA: http://www.nasa.gov/mission_pages/station/structure/elements/progress.html

NASA. (2011, August 19). *Shenzhou 4*. Retrieved September 11, 2011, from NASA NSSDC: http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2002-061A

NASA. (2011, August 19). *Shenzhou 5*. Retrieved September 11, 2011, from NASA NSSDC: http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2003-045A

NASA. (2011, August 19). *Shenzhou 6*. Retrieved September 11, 2011, from NASA NSSDC: http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2005-040A

NASA. (2011, August 19). *Shenzhou 7*. Retrieved September 11, 2011, from NASA National Space Science Data Center: http://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=2008-047A

NASA. (2012, July 20). *Shenzhou Spacecraft - Query Results*. Retrieved July 20, 2012, from NASA NSSDC: http://nssdc.gsfc.nasa.gov/nmc/spacecraftSearch.do

NASA. (2000, September 29). *Skylab Mission Goals*. Retrieved October 03, 2012, from NASA: http://www-pao.ksc.nasa.gov/kscpao/history/skylab/skylab-goals.htm

NASA. (2000, September 29). *Skylab Operations Summary*. Retrieved October 03, 2012, from NASA: http://www-pao.ksc.nasa.gov/kscpao/history/skylab/skylab-operations.htm

NASA. (2000, August 31). *Solid Rocket Boosters.* Retrieved October 07, 2012, from NASA: http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/srb.html

NASA. (2008, February 24). *Space Shuttle and International Space Station.* Retrieved September 23, 2012, from NASA: http://www.nasa.gov/centers/kennedy/about/information/shuttle_faq.html

NASA. (2011, September 27). *Space Shuttle Flights by Orbiter.* Retrieved October 07, 2012, from NASA: http://www.nasa.gov/mission_pages/shuttle/launch/orbiter_flights.html

NASA. (2011, August 03). *Space Shuttle Launches.* Retrieved October 07, 2012, from NASA: http://www.nasa.gov/pdf/537939main_ss-launches-080311.pdf

NASA. (2012, January 20). *Space Shuttle Overview: Atlantis (OV-104).* Retrieved October 07, 2012, from NASA: http://www.nasa.gov/centers/kennedy/shuttleoperations/orbiters/atlantis-info.html

NASA. (2008 , August 06). *Space Shuttle Overview: Challenger (OV-099).* Retrieved October 07, 2012, from NASA: http://www.nasa.gov/centers/kennedy/shuttleoperations/orbiters/challenger-info.html

NASA. (2005, January 31). *Space Shuttle Overview: Columbia (OV-102).* Retrieved October 07, 2012, from NASA: http://www.nasa.gov/centers/kennedy/shuttleoperations/orbiters/columbia_info.html

NASA. (2008, December 08). *Space Shuttle Overview: Discovery (OV-103).* Retrieved October 07, 2012, from NASA: http://www.nasa.gov/centers/kennedy/shuttleoperations/orbiters/discovery-info.html

NASA. (2008, December 08). *Space Shuttle Overview: Endeavour (OV-105).* Retrieved October 07, 2012, from NASA: http://www.nasa.gov/centers/kennedy/shuttleoperations/orbiters/endeavour-info.html

NASA. (2011, July 28). *Space Shuttle Vehicle Structure.* Retrieved October 07, 2012, from NASA: http://www.nasa.gov/mission_pages/shuttle/vehicle/index.html

NASA. (2011, March 02). *Spinoff flyer series*. (J. Jones, Editor) Retrieved July 17, 2011, from NASA Spinoff: http://www.sti.nasa.gov/tto/flyers.html

NASA. (2007, November 22). *STS-110 International Space Station.* Retrieved October 07, 2012, from NASA: http://www.nasa.gov/missions/highlights/webcasts/shuttle/sts110/iss-qa.html

NASA. (2011, February). *STS-133 Press Kit.* Retrieved July 31, 2011, from NASA: http://www.nasa.gov/pdf/491387main_STS-133%20Press%20Kit.pdf

NASA. (2011, April). *STS-134 Press Kit.* Retrieved July 31, 2011, from NASA: http://www.nasa.gov/pdf/538352main_sts134_presskit_508.pdf

NASA. (2011, July). *STS-135 Press Kit.* Retrieved July 31, 2011, from NASA: http://www.nasa.gov/pdf/566071main_135_press_kit2.pdf

NASA. (2006, March 05). *The Orbiter.* Retrieved October 07, 2012, from NASA: http://www.nasa.gov/returntoflight/system/system_Orbiter.html

NASA, & SpaceX. (2012, August 02). *Space Exploration Technologies (SpaceX) Space Act Agreement.* Retrieved September 22, 2012, from NASA: http://commercialcrew.nasa.gov/document_file_get.cfm?docid=633

Nimura, K., Goto, T., Kondo, S., Egawa, K., Nakamura, T., & Arita, M. (2008, Dec). *Development Status of the H-IIB Launch Vehicle.* Retrieved May 08, 2012, from Mitsubishi Heavy Industries, Ltd.: http://www.mhi.co.jp/en/technology/review/pdf/e454/e454016.pdf

Norris, G. (2011, May 02). *Sierra Nevada Details Drop Plan For Dream Chaser.* Retrieved January 08, 2012, from *Aviation Week*: http://www.aviationweek.com/aw/generic/story_channel.jsp?channel=space&id=news/asd/2011/05/02/02.xml&headline=Sierra%20Nevada%20Details%20Drop%20Plan%20For%20Dream%20Chaser

Orbital Sciences Corporation. (n.d.). *Artist rendering of Cygnus spacecraft.* Retrieved July 29, 2012, from Orbital Sciences Corporation: http://www.orbital.com/images/High/Cygnus_ISS_Hi.jpg

Orbital Sciences Corporation. (2012, July). *Cargo Resupply Services - Updates.* Retrieved July 29, 2012, from Orbital Sciences Corporation: http://www.orbital.com/CargoResupplyServices/

Orbital Sciences Corporation. (2013, April 21). *Orbital Successfully Launches First Antares Rocket.* Retrieved July 20, 2013, from Orbital Sciences Corporation: http://www.orbital.com/NewsInfo/release.asp?prid=852

Orbital Sciences Corporation. (2012). *Cygnus Fact Sheet.* Retrieved July 29, 2012, from Orbital Sciences Corporation: http://www.orbital.com/NewsInfo/Publications/Cygnus_fact.pdf

Perrett, B. (2012, March 12). *China Working On Big Range Of Space Engines.* Retrieved May 07, 2012, from *Aviation Week & Space Technology*: http://www.aviationweek.com/Article.aspx?id=/article-xml/AW_03_12_2012_p32-433971.xml#

Perrett, B. (2010, March 15). *Longer Marches.* Retrieved September 06, 2010, from *Aviation Week*: http://www.aviationweek.com/Article.aspx?id=/article-xml/AW_03_15_2010_p22-211145.xml&headLine=Longer%20Marches

Perrotto, T. J., & Byerly, J. (2012, May 31). *SpaceX Dragon Capsule Returns To Earth After First Commercial Flight To Space Station.* Retrieved June 17, 2012, from NASA: http://www.nasa.gov/home/hqnews/2012/may/HQ_12-179_SpaceX_Splashdown.html

Portree, D. S. (1995, March). *Mir Hardware Heritage.* Retrieved July 31, 2011, from NASA: http://ston.jsc.nasa.gov/collections/TRS/_techrep/RP1357.pdf

Public Broadcasting Service. (2005, October 06). *Timeline: the Space Race.* Retrieved September 30, 2012, from Public Broadcasting Service (PBS): http://www.pbs.org/wgbh/amex/moon/timeline/index.html

Reiley, K., Burghardt, M., Wood, M., Ingham, J., & Lembeck, M. F. (2011). *Design Considerations for a Commercial Crew presented at AIAA Space 2011.* Retrieved March 25, 2012, from The Boeing Company: http://www.boeing.com/defense-space/space/ccts/docs/Space_2011_Boeing.pdf

RIA Novosti. (2010, September 21). *Soyuz spacecraft upgrade ups payload by 70 kg.* Retrieved July 31, 2011, from RIA Novosti: http://en.rian.ru/science/20100921/160672513.html

RIA Novosti. (2011, March 03). *The Soyuz TMA-M, a new version of the legendary spacecraft.* Retrieved July 31, 2011, from RIA Novosti: http://en.rian.ru/infographics/20110303/162841261.html

Shanklin, E. (2009, July 29). *SpaceX Completes Qualification of Falcon 9 First Stage Tank and Interstage.* Retrieved June 17, 2012, from SpaceX: http://www.spacex.com/press.php?page=20090729

Sierra Nevada Company. (2011, June 24). *SNC Space Systems - Recent News & Press Release*. Retrieved December 29, 2011, from Sierra Nevada Company: http://sncspace.com/press_more_info.php?id=318

Sierra Nevada Corporation. (2010, December 15). *Sierra Nevada News & Press Releases*. Retrieved January 07, 2012, from Sierra Nevada Corporation: http://www.sncorp.com/press_more_info.php?id=433

Sierra Nevada Corporation. (2011). *SNC Space Exploration Systems*. Retrieved January 08, 2012, from Sierra Nevada Corporation: http://www.spacedev.com/space_exploration.php

Sierra Nevada Corporation Space Systems. (n.d.). *Dream Chaser.* Retrieved December 29, 2011, from Sierra Nevada Corporation: http://sncspace.com/uploads/brochures/Dream_Chaser.pdf

Space Exploration Technologies Corp. (2012). *Dragon.* Retrieved September 22, 2012, from SpaceX: http://www.spacex.com/dragon.php

Space Exploration Technologies Corp. (2010). *Dragon Overview*. Retrieved September 31, 2010, from SpaceX: http://www.spacex.com/dragon.php

Space Exploration Technologies Corp. (2013, March 26). *SpaceX - Updates.* Retrieved July 20, 2013, from SpaceX: http://www.spacex.com/updates.php

SpaceX. (2012). *Dragon.* Retrieved August 24, 2012, from Space Exploration Technologies: http://www.spacex.com/dragon.php

SpaceX. (n.d.). *DragonLab Datasheet.* Retrieved August 24, 2012, from Space Exploration Technologies: http://www.spacex.com/downloads/dragonlab-datasheet.pdf

SpaceX. (2012). *Falcon 9.* Retrieved June 17, 2012, from SpaceX: http://www.spacex.com/falcon9.php

SpaceX. (2012). *Falcon Heavy.* Retrieved June 17, 2012, from SpaceX: http://www.spacex.com/falcon_heavy.php

SpaceX. (2012, June 01). *SpaceX - Updates.* Retrieved June 17, 2012, from SpaceX: http://www.spacex.com/updates.php

Svitak, A. (2012, May 21). *Budget Pressures Prompt ISS Partners To Justify Costs.* Retrieved September 23, 2012, from *Aviation Week & Space Technology*: http://www.aviationweek.com/Article.aspx?id=/article-xml/AW_05_21_2012_p22-458840.xml&p=1#

Teague, K. (2007 йил 2-March). *Apollo-Soyuz Diagrams*. Retrieved 2010 йил 31-Dec from NASA History Program Office: http://history.nasa.gov/diagrams/apol_soyuz.htm

Teague, K. (2007, March 28). *Project Apollo Diagrams*. Retrieved November 28, 2010, from NASA: http://www.hq.nasa.gov/office/pao/History/diagrams/apollo.html

Thomas, C., & Perrotto, T. (2012, August 03). *RELEASE : 12-263: NASA Announces Next Steps in Effort to Launch Americans from U.S. Soil.* Retrieved September 22, 2012, from NASA: http://www.nasa.gov/centers/kennedy/news/releases/2012/release-20120803.html

Tyson, N. d. (2012). *Space Chronicles: facing the ultimate frontier* (First ed.). (A. Lang, Ed.) New York, NY: W. W. Norton & Company, Inc.

U.S. Air Force. (2010, April 23). *Air Force officials launch Atlas V carrying X-37B Orbital Test Vehicle.* Retrieved September 16, 2012, from U.S. Air Force: http://www.af.mil/news/story.asp?id=123201234

U.S. Air Force. (2011, March 03). *Factsheets: X-37B Orbital Test Vehicle.* Retrieved September 16, 2012, from U.S. Air Force: http://www.af.mil/information/factsheets/factsheet.asp?id=16639

U.S. Human Spaceflight Plans Committee. (2009). *Review of U.S. Human Spaceflight Plans Committee - Final Report* . Retrieved March 08, 2010, from NASA: http://www.nasa.gov/pdf/396093main_HSF_Cmte_FinalReport.pdf

United Launch Alliance. (2010, March). *Atlas V Launch Services User's Guide.* Retrieved April 21, 2012, from United Launch Alliance, LLC: http://www.ulalaunch.com/site/docs/product_cards/guides/AtlasVUsersGuide2010.pdf

United Launch Alliance. (2010). *Atlas V Product Card.* Retrieved April 21, 2012, from United Launch Alliance, LLC: http://www.ulalaunch.com/site/docs/product_cards/AV_product_card.pdf

United Launch Alliance. (2007, September). *Delta IV Payload Planner Guide.* Retrieved April 21, 2012, from United Launch Alliance, LLC.:

http://www.ulalaunch.com/site/docs/product_cards/guides/DeltaIVPayloadPlannersGuide2007.pdf

United Launch Alliance. (2010). *Delta IV Product Card.* Retrieved April 21, 2012, from United Launch Alliance, LLC.: http://www.ulalaunch.com/site/docs/product_cards/DIV_product_card.pdf

Williams, D. R. (2003, December 11). *Apollo 18 through 20*. Retrieved July 24, 2011, from National Space Science Data Center: http://nssdc.gsfc.nasa.gov/planetary/lunar/apollo_18_20.html

Zak, A. (2011, April 04). *Prospective Piloted Transport System.* Retrieved April 15, 2012, from Russian Space Web: http://www.russianspaceweb.com/ppts.html

Zak, A. (2009, April 03). *Russia to unveil spaceship plans.* Retrieved April 15, 2012, from BBC News: http://news.bbc.co.uk/2/hi/science/nature/7980824.stm

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